An Ecological Approach to Sensory Substitution

Tesis

presentada por

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A Manuel,
que vale más que un cortijo.

We don't simply see, we look.

E.J. Gibson

In other words, the real beginning is with the act of seeing, it is looking, and not a sensation of light.

J. Dewey

Consider a fire —that is, a terrestrial event with flames and fuel. It is a source of four kinds of stimulation, since it gives off sound, odor, heat, and light. It crackles, smokes, radiates in the infrared band, and radiates or reflects in the visible band (...). One can hear it, smell it, feel it, and see it, or get any combination of these detections, and thereby perceive a fire. Vision provides the most detailed information with unique colors, shapes, textures, and transformations, but any one of the others will also serve. For this event, the four kinds of stimulus information and the four perceptual systems are *equivalent*.

J.J. Gibson

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(...) gonna try with a little help from my friends.

The Beatles

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Abstract

Touch is the most crucial perceptual system for humans. It is highly related to our possibilities to survive and it is, together with audition, the preferred system to compensate the absence of vision in everyday life. The possibilities of touch have been studied in the context of sensory substitution; that is, when one perceptual modality, typically vision, is substituted by another one. The number of haptic devices that are designed to help visually-impaired people or professionals working in low-vision conditions has been considerably growing during the last 50 years. However, compared to the number of possible users, just very few of them are either available or daily used.

The aim of this dissertation is to assess if ecological psychology offers a better framework than mainstream approaches to deal with essential features in the design and test of new sensory substitution devices. Some examples of these features involve the role of exploration, learning, mental representations, and information. In order to do so, I present a group of five empirical studies in which four different devices have been used: Three of these devices were related to the TSIGHT and the fourth one was the Enactive Torch. A total of nine experiments were conducted in three research facilities. The experimental tasks included detecting and stepping on obstacles, judging the climbability of an obstacle, orienting and approaching to a target, and steering towards a target avoiding multiple obstacles and selecting routes. A wide variety of experimental conditions that ranged from totally absence of vision and low-vision conditions to full visual training were tested. Research designs included a pretest-posttest design, a within-subject design, and several factorial designs. Blindfolded and blind adults with ages that varied from 18 to 65 years old participated in this research. In all cases, position and orientation of participants during the tasks were recorded using a motion capture system (either Optotrak Certus, Northern Digital Inc., Canada; or Qualisys Inc., Sweden). In

addition to performance variables, movement variables like velocity, range of movements, and number and amplitude of oscillations were studied. Also, simulations of a dynamic information-based control model for route selection were performed and compared to results of participants using a haptic device.

Results of the experiments indicated that it was possible to solve all tasks using haptic devices even when they were not placed on an area of maximum sensitivity (for instance, a device was placed on the lower leg). The relevant role of exploration and active perception was confirmed in several studies and its relation to accuracy was also documented.

Furthermore, results revealed that task-specific information is an essential part of sensory substitution. Consequently, it was argued that it could be an explanation of the low-applicability of sensory substitution devices. Finally, evidence in favor of the dynamic information-based control model for route selection against hypothesis involving mental representations were found. My conclusion supports that ecological psychology provides researchers with a better framework to deal with sensory substitution. This approach suggests innovative solutions that could be of great relevancy for visually-impaired people.

Resumen

El tacto es el sistema perceptivo más crucial para los seres humanos. Está altamente relacionado con nuestras posibilidades de supervivencia y es, junto con la audición, el sistema preferido para compensar la ausencia de visión en la vida diaria. Las posibilidades del tacto han sido estudiadas en el contexto de la sustitución sensorial, es decir, cuando una modalidad sensorial, típicamente la visión, es sustituida por otra. El número de dispositivos hápticos que están diseñados para ayudar a las personas con discapacidad visual o a profesionales que trabajan en condiciones de baja visión ha ido aumentando durante los últimos 50 años. Sin embargo, comparado con el número de posibles usuarios, muy pocos de estos dispositivos están disponibles o son usados diariamente.

El objetivo de esta tesis es evaluar si la psicología ecológica ofrece un marco mejor que las aproximaciones convencionales para lidiar con características indispensables del diseño y de las pruebas de nuevos dispositivos de sustitución sensorial. Algunos ejemplos de estas características incluyen el papel de la exploración, el aprendizaje, las representaciones mentales y la información cuando usamos dispositivos hápticos. Para ello, presento un grupo de cinco estudios empíricos en los cuales han sido usado cuatro dispositivos diferentes. Tres de estos dispositivos estaban relacionados con el TSIGHT y el cuarto fue la Enactive Torch. Se llevaron a cabo un total de nueve experimentos en tres centros de investigación diferentes. Las tareas experimentales incluyeron detectar y pisar sobre un escalón, juzgar la escalabilidad de un obstáculo, orientarse y aproximarse a un objetivo y dirigirse a un objetivo evitando múltiples obstáculos y seleccionando rutas. Se pusieron a prueba una amplia variedad de condiciones experimentales que iban desde la ausencia de visión y la baja visión hasta el entrenamiento con visión completa. Los diseños experimentales incluyeron un diseño pretest-posttest, un diseño intrasujeto y varios diseños factoriales. Adultos con los ojos tapados y adultos con ceguera con

edades comprendidas entre los 18 y los 65 años participaron en esta investigación. En todos los casos, la posición y la orientación de los participantes durante las tareas fue grabada usando un sistema de captura del movimiento (Optotrak Certus, Northern Digital Inc., Canadá; o Qualisys Inc., Suecia). Además de las variables de ejecución, se estudiaron variables de movimiento como velocidad, rango del movimiento y número y amplitud de las oscilaciones. También, se llevaron a cabo simulaciones de un modelo de dinámico basado en la información para la selección de rutas y sus resultados fueron comparados con el resultado de los participantes usando un dispositivo háptico.

Los resultados de los experimentos indicaron que era posible resolver todas las tareas usando dispositivos hápticos incluso cuando no están colocados en las áreas de máxima sensibilidad (por ejemplo, un dispositivo fue colocado sobre la espinilla). La importancia de la exploración y la percepción activa fue confirmada en varios estudios y su relación con la precisión también fue documentada.

Además, los resultados revelaron que la información específica para la tarea es una parte esencial de la sustitución sensorial. Consecuentemente, se argumenta que puede ser una explicación de por qué hay una baja aplicabilidad de los dispositivos de sustitución sensorial. Finalmente, se encontró evidencia en favor del modelo dinámico basado en la información para la selección de rutas contra las hipótesis que involucran representaciones mentales. Mi conclusión apoya que la psicología ecológica provee a los/las investigadores/as con un marco mejor para tratar la sustitución sensorial. Esta aproximación sugiere soluciones innovadoras que podrían ser de gran relevancia para las personas con discapacidad visual.

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Capítulo 1

Introducción

"La perspectiva gibsoniana (1966) del aprendizaje perceptivo probablemente predeciría que, en la medida en que una matriz táctil contenga las mismas adyacencias temporales y espaciales que se encuentran en la matriz óptica, aprender a responder a 'los invariantes de alto orden' en la estimulación táctil no debería presentar ninguna dificultad abrumadora ".

(White, Saunders, Scadden, Bach-Y-Rita y Collins, 1970)

1.1 ¿Por qué estudiar sustitución sensorial desde una aproximación ecológica?

El tacto, esto es, el sistema háptico, es un sistema perceptivo extraordinario para los humanos. Consiste en una variedad de subsistemas como el tacto cutáneo, el tacto dinámico, o el dolor (Gibson, 1966), tan esenciales que la ausencia de tacto es incompatible con la vida. Es posible encontrar gente que es completamente ciega, que no puede oír, sin gusto, o diagnosticada con anosmia; pero no hay personas que hayan perdido completamente el tacto. Obviamente, es posible detectar problemas en el tacto. La mayoría de estos problemas están relacionados con la sensibilidad cutánea, como la percepción de texturas (por ejemplo, en personas con diabetes, ver Travieso y Lederman, 2007), o diferentes niveles de desaferenciación, como el caso de la neuropatía periférica (Carello, Kinsella-Shaw, Amazeen y Turvey, 2006; Fleury y col., 1995). Aunque menos común que los problemas de sensibilidad, otros subsistemas pueden ser severamente disfuncionales y tener un impacto profundo en la calidad de vida de la gente afectada: ese es el caso del dolor. Para ilustrar esta situación, quiero referirme a unos pocos casos que existen de personas diagnosticadas con 'indiferencia congénita al dolor'. Las personas que reciben este diagnóstico normalmente mueren durante su infancia debido a heridas severas o a enfermedades no tratadas; pero aquellos que sobreviven preservan la habilidad de distinguir, por ejemplo, temperatura y propiocepción (Cox y col., 2006) o, por lo menos, su enfermedad solamente afecta a algunas partes de sus cuerpos. Así, el tacto parece ser el sistema perceptivo más crucial para los humanos.

Aunque la importancia del tacto puede no haber sido siempre reconocida como se merece (Klatzky y Lederman, 2001), un buen número de investigadores en psicología han afirmado que el tacto es tan útil que incluso puede ser un candidato adecuado para compensar la pérdida de visión. Típicamente, las personas con discapacidad visual se apoyan en el bastón blanco o utilizan un perro–guía para la navegación autónoma, pero estas ayudas para la movilidad han mostrado algunas desventajas (Shoval, Ulrich y Borenstein, 2003). Por un lado, el entrenamiento de un perro-guía es muy caro. En 2003, Shoval y colaboradores informaron de costes que oscilaban entre 12000 y 20000 US$, un rango que coincide con los 17000 US$ que indicaron Durette, Louveton, Alleysson y Hérault (2008). Más aún, el periodo en el que un perro puede guiar a usuarios ciegos varía de cinco a ocho años, después del cual se necesita normalmente otro perro-guía. Por otro lado, el bastón blanco es la ayuda de navegación más extendida (Dakopoulos y Bourbakis, 2010), pero el área que se explora con él solamente es de 1 metro alrededor del usuario y a una altura muy baja, lo cual deja mucho espacio sin explorar y, consecuentemente, sin percibir (Durette y col., 2008).

Teniendo en cuenta la importancia del tacto y la escasez de ayudas disponibles para los ciegos, es razonable comprender por qué los investigadores tenían esperanzas en las posibilidades de usar nuevas tecnologías para sustituir la visión a través del sistema háptico. Por ejemplo, en un estudio temprano, Geldard (1960) afirmó que la piel podría hacer discriminaciones tanto temporales como espaciales que serían útiles en una tarea de lectura con un dispositivo vibrotáctil. Von Haller (1966, pág. 3) afirmó que el tacto está "raramente ocupado" y que ofrece "una oportunidad de ingeniar un lenguaje” en términos de codificación y procesamiento de información.

Después de los ejemplos mencionados arriba desde el campo de la comunicación, la investigación en sustitución sensorial táctil se centró en el reconocimiento de formas con el famoso trabajo de Bach-y-Rita, Collins, Saunders, White y Scadden (1969) y el guiado del movimiento (Jansson, 1983). Sin embargo, aproximaciones recientes han considerado que las capacidades de procesamiento del tacto asociadas con las superficies receptoras no son suficientes para lidiar con las altas variaciones espaciotemporales de la estimulación que son necesarias para una auténtica sustitución que vaya de lo visual a lo háptico (Spence, 2014). Por el contrario, otros autores desde la aproximación enactivista defienden que las contingencias sensoriomotrices que pueden establecerse entre las sensaciones y el movimiento son la base para la sustitución sensorial y el tacto podría ser un candidato suficiente para complementar la visión (Lenay, Gapenne, Hanneton, Marque y Genouëlle, 2003).

En esta tesis doctoral, sugiero que el modo de usar el tacto apropiadamente para sustituir la visión se fundamenta en rasgos de la información ecológica, como el concepto de especificidad, affordance y el bucle percepción-acción. Estos conceptos están englobados en una aproximación teórica conocida como psicología ecológica, un campo de investigación iniciado por J. J. Gibson a mediados del siglo XX.

La psicología ecológica ha crecido desde el trabajo pionero de Gibson, sostenido por un sólido programa de investigación experimental. Algunos campos con hallazgos importantes proporcionados desde la aproximación ecológica son la psicología del deporte, el tacto dinámico, la rehabilitación clínica, la ergonomía y la robótica, entre otros. Aunque la aproximación ecológica ha estado históricamente relacionada con la percepción, estudios más recientes han extendido el trabajo más allá de esta área al aprendizaje (Jacobs y Michaels, 2007; Michaels, Arzamarski, Isenhower y Jacobs, 2008) o la coordinación social (Marsh, Richardson y Schmidt, 2009), por ejemplo. Esos resultados, junto con los resultados obtenidos desde perspectivas como el enactivismo y la aproximación sensoriomotriz, desafían la visión cognitivista que ha sido convencional en las ciencias cognitivas. En este sentido, hay razones para pensar que la investigación en sustitución sensorial desde una aproximación ecológica podría ofrecer resultados importantes en la práctica clínica, el diseño tecnológico y, por supuesto, implicaciones teóricas en las Ciencias Cognitivas.

1.2 Objetivo principal

El objetivo de esta tesis doctoral es comprobar si la psicología ecológica, como se explica en el capítulo 2, ofrece un mejor marco para diseñar e implementar la sustitución sensorial y proponer soluciones innovadoras a problemas que llevan mucho tiempo presentes en este campo de investigación. Para conseguir este objetivo, mostraré una serie de experimentos hechos con dispositivos de sustitución sensorial (SSDs) que abordan problemas específicos de este campo de investigación y algunas respuestas a estos problemas planteados. Las preguntas, experimentos y conclusiones comentadas en esta tesis doctoral están inspirados por la aproximación ecológica y también por teorías antirrepresentacionales las cuales se han extendido en lo que se ha llamado 'la era post-conexionista'(Calvo y Symons, 2014).

Desde la percepción al aprendizaje, incluyendo tareas como detección de obstáculos y navegación espacial, se revisan varios temas y se discuten trabajos tanto teóricos como empíricos. El trabajo empírico tuvo lugar en tres instalaciones diferentes: el laboratorio del Grupo de Investigación en Percepción y Movimiento (Universidad Autónoma de Madrid), el Movement Innovation Lab (Queen's University of Belfast) y el Center for Cognition, Action, and Perception (University of Cincinnati). Se usaron cuatro dispositivos hápticos. Los tres primeros son el producto de las ideas originales del Grupo de Investigación en Percepción y Movimiento (Universidad Autónoma de Madrid) en colaboración con el Grupo de Investigación de Robótica y Cibernética (Universidad Politécnica de Madrid) y son prototipos que llevaron a, o fueron desarrollados desde, el sistema de sustitución sensorial llamado TSIGHT. El cuarto dispositivo fue la Enactive Torch, un dispositivo vibrotáctil desarrollado por Tom Froese y Adam Spiers (actualmente en la Universidad Nacional Autónoma de México y la Universidad de Yale, respectivamente) que ha sido usado para diferentes experimentos en el Center for Cognition, Action, and Perception (University of Cincinnati).

1.3 Organización de esta tesis

Esta tesis doctoral tiene la siguiente organización:

En el capítulo 2, me centro en los antecedentes teóricos. Primero, escribo una revisión de la literatura especializada en el campo de la sustitución sensorial ofreciendo un breve estado de la cuestión en términos de SSDs vibrotáctiles y auditivos que son relevantes para esta tesis doctoral. El principal énfasis se hace en los dispositivos vibrotáctiles, pero se mencionan algunos dispositivos visual-a-auditivo cuando se requiere por razones metodológicas o teóricas. En la segunda parte del capítulo 2, sección 2.2, página 32, explico la aproximación ecológica considerando, de manera más detallada, cuáles son los conceptos clave que son aplicables en la sustitución sensorial. Para adelantar el contenido de la sección 2.2, estos conceptos clave son 'affordance', 'especificidad', 'bucle percepción-acción' y 'aprendizaje directo'. Finalmente, en la sección 2.3, introduzco unos pocos ejemplos de dispositivos de sustitución sensorial que están relacionados con la psicología ecológica.

En el capítulo 3, presento el primer experimento de esta tesis doctoral. Este experimento se llevó a cabo usando un novedoso dispositivo vibrotáctil que se coloca en la parte baja de la pierna. El objetivo de este estudio era triple: primero, se intentó comprobar si era posible pisar sobre obstáculos con este tipo de dispositivo. Segundo, parecía importante tratar el problema de la práctica y el entrenamiento con un SSD, comprobando si la experiencia tiene un papel esencial en la ejecución de esta tarea. Y tercero, intentamos determinar si practicar con el dispositivo en diferentes condiciones tenía efectos distintos en la ejecución.

En el capítulo 4, la atención se centra en el concepto de affordance y su aplicación a la investigación en sustitución sensorial. En el experimento de este capítulo, la affordance seleccionada era la escalabilidad de un obstáculo, esto es, una affordance, escalada corporalmente, que era percibida solamente a través de un SSD háptico. El principal objeto de este experimento era el proceso de atribución distal. La lógica que subyace a este estudio es la siguiente: si una affordance puede percibirse a través de visión normal y de sustitución sensorial, entonces no hay razón para negar que el proceso de atribución distal, que típicamente se asume en la visión, debería asumirse también en la sustitución sensorial.

En el capítulo 5, se usa una versión sofisticada de dispositivos previos en una serie de experimentos que incluyen orientarse, aproximarse, y dirigirse hacia un objetivo. El pilar de este capítulo es la información provista a través de un SSD y, por ello, la especificidad, tal y como se define en la aproximación ecológica. Se ofrecen tres razones para la baja difusión de SSDs entre las personas con discapacidad visual. Dos de ellas pueden encontrarse en la literatura científica que mantiene un punto de vista cognitivista sobre la sustitución sensorial. Brevemente, estas razones son la sensibilidad limitada de las superficies receptoras y las restringidas capacidades de procesamiento cognitivo asociadas a la piel. La tercera razón emerge del marco ecológico y señala que una posible explicación es que en el diseño de SSDs no se ha tenido suficientemente en cuenta cómo la información especifica propiedades relevantes para la tarea. El principal objetivo de este experimento era comprobar si la última razón podría explicar, al menos en parte, la escasez de SSDs en la vida diaria.

El capítulo 6 es una extensión del último experimento señalado en el capítulo 5. Un grupo de participantes con discapacidad visual realizaron una tarea que consistía en dirigirse hacia un objetivo usando el SSD háptico desarrollado para el experimento previo. Se comprueba la utilidad de este dispositivo como Ayuda Electrónica de Navegación (ETA) para personas con ceguera y se compara la ejecución de estos participantes con los datos de ejecución de los participantes con los ojos tapados del capítulo anterior.

El capítulo 7 ofrece una aproximación innovadora a la sustitución sensorial considerando la complejidad de los SSD. Dos ideas principales guían este estudio. Primero, el uso de un SSD minimalista permitió comprobar la aproximación del control basado en la información para la selección de rutas. Esta aproximación no incluye representaciones mentales ni planificación, siendo un modelo útil desde la aproximación ecológica. Segundo, se probó un dispositivo minimalista para realizar una tarea de navegación que conlleva caminar hacia un objetivo evitando múltiples obstáculos en diferentes condiciones de ejecución (visión gravemente dañada y ausencia de visión). El experimento de este capítulo intenta también arrojar algo de luz sobre los requerimientos mínimos de los dispositivos vibrotáctiles usados como ETAs.

En el capítulo 8, discuto los resultados principales de los que se informa en capítulos previos, conectando estos resultados con los antecedentes teóricos presentados en el capítulo 2. Se resaltan algunas implicaciones a nivel teórico que puedan ser alentadoras para investigadores en ciencia cognitiva. También menciono varios resultados de experimentos en relación con recomendaciones técnicas que pueden ser útiles para personas con discapacidad visual. En la sección de limitaciones y trabajo futuro ofrezco varias líneas de investigación que surgen de este trabajo y que podrían mejorarlo.

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Chapter 1

Introduction

"The Gibsonian (1966) view of perceptual learning would probably predict that, to the extent a tactile array contained the same temporal and spatial adjacencies to be found in the optic array, learning to respond to "the higher order invariances" in tactile stimulation should present no overwhelming difficulty."

(White, Saunders, Scadden, Bach-Y-Rita, & Collins, 1970)

1.1 Why Study Sensory Substitution from an Ecological Approach?

Touch, that is, the haptic system, is an amazing perceptual system for humans. It consists of a variety of subsystems like cutaneous touch, dynamic touch, or pain (Gibson, 1966), so essential that the absence of touch is incompatible with life. It is possible either to find people that are completely blind, or that cannot hear at all, or without taste, or diagnosed with anosmia; but there are no people with a complete loss of touch. Obviously, it is possible to detect problems in touch. Most of these problems are related to cutaneous sensitivity like the perception of textures (for instance, in people with diabetes, see Travieso & Lederman, 2007), or different levels of de-afferentation, like the case of peripheral neuropathy (Carello et al., 2006; Fleury et al., 1995). Although less common than these sensitivity problems, other subsystems can be severely dysfunctional and have a profound impact on the quality of life of affected people: that is the case of pain. Just to illustrate this situation, there are a few cases of people diagnosed with ‘congenital indifference to pain’. People who receive this diagnosis usually die during their childhood due to severe injuries or not-treated illness; but those who survive preserve the ability to distinguish, for instance, temperature and proprioception (Cox et al., 2006) or, at least, their disorder only affects some parts of their bodies. Thus, in some sense, touch seems to be the most crucial perceptual system for humans.

Even though the importance of touch may not always have been recognized as it deserves (Klatzky & Lederman, 2001), a range of researchers in psychology have claimed that touch is so useful that it can even be a suitable candidate to compensate for the loss of vision. Typically, visually impaired people rely on white (long) canes or guide dogs for autonomous navigation, but these mobility aids have shown some disadvantages (Shoval et al., 2003). On one side, the training of a guide dog is expensive. In 2003, Shoval and colleagues reported costs between 12000 to 20000 US$, a range that coincides with the 17000 US$ mentioned by Durette et al. (2008). Furthermore, the period of a dog guiding blind users varies from five to eight years, after which another guide dog is usually needed. On the other side, the white cane is the most extended navigation aid (Dakopoulos & Bourbakis, 2010), but the explored area is only about 1 m around the user, and at a very low height, which leaves much space unexplored and, consequently, unperceived (Durette et al., 2008).

Taking into account the importance of touch and the scarce available aids for the blind, it is reasonable to understand why researchers were hopeful about the possibilities of using new technologies to substitute vision through the haptic system. For example, in an early study, Geldard (1960) claimed that the skin could make both temporal and spatial discriminations to be useful in a reading task performed with a vibrotactile device. Von Haller (1966, p. 3) claimed that touch is “rarely busy” and offers “a chance of actually engineering a language” in terms of coding and information processing.

After these examples from communication, research on tactile sensory substitution focused on shape recognition with the famous work of Bach-y-Rita et al. (1969) and on the tactile guidance of movement (Jansson, 1983). Nevertheless, recent approaches have considered that the cognitive-processing capabilities of touch associated with the receptor surfaces are not sufficient to deal with the high spatiotemporal variations of the stimulation that is mandatory for a true visual-to-tactile substitution (Spence, 2014). On the contrary, other authors from the enactive account defend that the sensorimotor contingencies that can be established between sensations and movement are the basis for sensory substitution and that touch can be a sufficient candidate to supplement vision (Lenay et al., 2003).

In this dissertation, I suggest that the way to appropriately use touch to substitute vision relies on features at the level of ecological information, like the concept of specificity, affordance, and the perception-action loop. These concepts are encompassed in a theoretical approach known as ecological psychology, a field of research started by J.J. Gibson in the middle of 20^{th} century.

Ecological psychology has grown from the pioneering work of Gibson and is sustained by a solid experimental research program. Some fields with important findings made from the ecological approach are sports psychology, dynamic touch, clinical rehabilitation, ergonomics, and robotics, among others. Although the ecological approach has been historically related to perception, more recent studies have extended experimental work beyond this area to learning (Jacobs & Michaels, 2007; Michaels et al., 2008) or social coordination (Marsh et al., 2009), for instance. Those findings, together with results obtained from perspectives such as enactivism and the sensorimotor approach, challenge the cognitivist view that has been mainstream in cognitive sciences. In this same vein, there is reason to think that research on sensory substitution from the ecological approach could offer important outcomes in clinical practice, technological design, and, of course, theoretical implications for the cognitive sciences.

1.2 Main Aim

The aim of this dissertation is to test whether ecological psychology, as explained in Chapter 2, offers a better framework to design and implement sensory substitution and to propose innovative solutions to long-standing problems in this research field. To achieve this aim, I report a series of experiments performed with Sensory

Substitution Devices (SSDs). The experiments address specific problems that are encountered in sensory substitution and possible ecological solutions to these problems. The questions, experiments, and conclusions referred to in this dissertation are inspired by the ecological approach and also by antirepresentational theories, which have been extended in what has been called the 'post-connectionist era' (Calvo & Symons, 2014).

From perception to learning, including tasks like obstacle detection and spatial navigation, several topics are reviewed and both empirical and theoretical work is discussed. The empirical work took place in three different facilities: the laboratory of the Perception and Action Research Group (Universidad Autónoma de Madrid), the Movement Innovation Lab (Queen's University of Belfast), and the Center for Cognition, Action, and Perception (University of Cincinnati). Four different haptic devices were used. The first three devices are the product of original ideas of the Perception and Action Research Group (Universidad Autónoma de Madrid) in collaboration with the Robotics and Cybernetics Research Group (Universidad Politécnica de Madrid), and they are prototypes that led to, or were developed from, the SSD named TSIGHT. The fourth device is the Enactive Torch, a vibrotactile display developed by Tom Froese and Adam Spiers (currently at the Universidad Nacional Autónoma de México and Yale University, respectively) that has been used for different experiments at the the Center for Cognition, Action, and Perception (University of Cincinnati).

1.3 Organization of the Dissertation

In Chapter 2, I focus on the theoretical background. First, I include a review of the specialized literature in the field of sensory substitution, offering a brief state of the art in terms of the vibrotactile and auditory SSDs that are relevant for this dissertation (Section 2.1). The emphasis is on vibrotactile devices, but several visual-to-auditory devices are mentioned when this is required for methodological or theoretical reasons. In the second part of the chapter, Section 2.2, page 32, I explain the ecological approach considering, in a more detailed way, which are the key concepts of the approach that are applicable in sensory substitution. To anticipate the content of Section 2.2, these core concepts are 'affordance', 'specificity', 'perception-action loop', and 'direct learning'. Finally, in Section 2.3, I introduce a few examples of SSDs that are related to ecological psychology.

In Chapter 3, I present the first experiment of this dissertation. This experiment was performed with a novel haptic device that was placed on the lower leg. The goal of this study was threefold: First, it was intended to test if it was possible to step on obstacles with this type of device. Second, it seemed important to address the problem of practice and training with a SSD, checking if experience has an essential role in the execution of this task. And third, we intended to determine if different practice conditions have different effects on performance.

In Chapter 4, the focus of attention is on the concept of affordance and its application to research on sensory substitution. In the experiment of this chapter, the selected affordance was the climbability of steps, that is, a body-scaled affordance, which was perceived only through a haptic SSD. The object of study of this experiment was the process of distal attribution. The rationale behind this study is the following: if an affordance can be perceived both through normal vision and through vibrotactile sensory substitution, then, there is no reason to deny that the process of distal attribution that is typically claimed to happen in vision should be applied in the case of sensory substitution as well.

In Chapter 5, a sophisticated version of previous devices is used in a series of experiments involving orientation, approaching, and walking toward a target. The cornerstone of this chapter is the information provided through a SSD and, therefore, the concept of specificity as defined in the ecological approach. Three reasons for the low use of SSDs among visually-impaired people are provided. Two of them can be found in the scientific literature that maintains a cognitivist point of view about sensory substitution. Briefly, these reasons are the limited sensitivity of the receptor surfaces and the restricted cognitive processing capabilities associated with the skin. The third reason emerges from the ecological framework and points out that a possible explanation is that the design of SSDs does not sufficiently take into account how information specifies task-relevant properties. The main aim of this experiment was to the test if the latter reason could explain, at least in part, the shortage of SSDs in everyday life.

Chapter 6 is an extension of the last experiment reported in Chapter 5. A group of visually-impaired participants performed a task that consisted in steering toward a target using the haptic SSD developed for the previous series of experiments. The usefulness of this device as Electronic Travel Aid (ETA) for blind people is tested and their performance is compared with data from blindfolded participants.

Chapter 7 offers an innovative approach to sensory substitution regarding the complexity of SSD. Two main ideas guided this study. First, the use of a minimalist SSD allowed the test of the information-based control approach to route selection. This approach does not involve mental representations and planning, being a useful model from the ecological approach to cognition. Second, a minimalist device is tested in a navigation task which involved walking toward a target avoiding multiple obstacles in different performance conditions (severe impaired vision and absence of vision). The experiment reported in this chapter is also intended to shed some light about the minimum requirements of vibrotactile devices used as ETAs.

In Chapter 8, I discuss the main results reported in previous chapters, connecting these results with the theoretical background presented in Chapter 2. Some implications at the theoretical level that could be encouraging for researchers in cognitive science are highlighted. I also mention several outcomes of the experiments in relation to technological recommendations that can be useful for people with visually impairments. In the section of limitations and future work (Section 8.3), I provide several lines of research that arise from this work and could improve it.

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Chapter 2

Theoretical Background

In this chapter, the theoretical background is divided in three different sections. The first section reviews the field of sensory substitution mentioning relevant devices and experiments published in the past 50 years. I delve into three topics that are especially relevant in this dissertation: practice with SSDs, the notion of distal attribution, and the different kinds of information used in SSDs. The second section of this chapter describes the main concepts of ecological psychology, which is the theoretical approach that inspires this dissertation. These core concepts are 'affordance', 'specificity', 'perception-action loop', and 'direct learning'. The third section details the intersection between the ecological approach and sensory substitution regarding both empirical and theoretical points.

2.1 Sensory Substitution

2.1.1 Early Sensory Substitution Studies

The use of other modalities to compensate the loss of vision has been very common for centuries. Visually-impaired people frequently rely on their non-visual perceptual systems in everyday life, in particular on touch and hearing, to identify voices, guide themselves through spaces, and recognize shapes of objects, among others.

Since the beginning of the 20^{th} century the interest in new devices for the blind started to grow. Reviews about SSDs usually start with devices that were built in the seventies, but long before that, in 1897, a Polish scientist named Noiszewski built a device called 'elektroftalm', which used photosensitive elements (basically selenium) to transform light into sounds (Starkiewicz & Kuliszewski, 1963). A blind person could use, through earphones, this original device to hear sounds that indicated the existence of a source of light, like a lamp or a window. This first elektroftalm was later updated into a haptic device by Starkiewicz and Kuliszewski (1963). The original device remained unknown in other parts of Europe and the US, and a few years later, a device that seemed to function in a similar way was reported with the name of 'Optophone' (D'Albe, 1914). This device emitted sounds (musical frequencies) based on the shape of printed letters, but it did not succeed in being sold among visually-impaired people. This device was the first-reported reading aid for the blind, a kind of device that became more relevant with the years. Two reasons for this relevance can be stated: The Braille system invented during the first part of the 19^{th} century had been spread across the world, and the number of blind children attending public schools increased considerably (Lowenfeld, 1956). The superiority of Braille or embossed letters for teaching was controversial at that time (Farrell, 1956).

In this historical context, the possibilities of touch to substitute vision for some tasks related to communication were on the table. Geldard (1960) reflected this situation in his work, where he wondered about the limits of the skin to be used in communication: "Howell, working in our laboratory, found that seven vibrators could be spaced on the ventral rib cage with 100-percent identifiability of locus, under his conditions. This is perhaps the limit for a practical cutaneous communication system" (Geldard, 1960, p. 1548). Six years later, Linvill and Bliss (1966) described the functioning of a device that was later known as 'Optacon' (optical-to-tactile converter), a marketed reading aid that improved the device used by Geldard, who named his device 'the Optohapt' (Geldard, 1966). During the next decades, the studies published with the Optacon changed the approach from engineering to psychology, focusing on haptic perception and psychophysics (some examples can be found in Craig, 1976; and Epstein, Hughes, Schneider, & Bach-y-Rita, 1989).

Although those studies with the Optacon and the Optohapt influenced the research made in the following years (White et al., 1970), sensory substitution started to be a new research field thanks to the widely-known work of Paul Bach-y-Rita. His publications with the Tactile Vision Sensory Substitution (TVSS) have been cited thousands of times[1] and his research was prolonged for almost 40 years. The TVSS (Bach-y-Rita et al., 1969) was not the first visual-to-tactile device, but it was the first attempt to use a vibrotactile device to substitute vision as a whole perceptual system instead of replacing vision in specific tasks. In a prominent study entitled 'Seeing with the skin', Bach-y-Rita and colleagues stated that: "It is surprising that in this day of advanced technology, the blind are still moving about in the world using a cane, a guide dog, a sighted companion, or an outstretched hand."(White et al., 1970, p. 23). Leaving apart the validity of this assertion nowadays, the main contribution of Bach-y-Rita and colleagues was the idea behind the (currently known as) general-purpose devices (Loomis, Klatzky, & Giudice, 2012). This idea was extended in a variety of experiments including the perception of line orientation, shape recognition, and face identification (Bach-y-Rita et al., 1969; Bach-y-Rita, 1975).

The first version of the TVSS was built in the back of a 'dental chair' (Bach-y-Rita et al., 1969). It consisted of a camera, a commutator, and a matrix of tactors. The camera picked up the luminosity of an image that was transformed with the commutator in 400 points of on-and-off stimulation through the tactors. There was no possibility of intermediate vibrations in what can be defined as a black and white image projection. Other versions of the TVSS included changes in the camera and the place of the matrix of tactors, but the basic functioning of the device remained intact.

There are two interesting reports of Guarniero (1977, 1974) describing his experience with the TVSS from the perspective of a congenitally blind person. He practiced with the device in two periods of three weeks each time, with a separation of 17 months between periods. In these studies, the functioning of the device and the training programs were described. In the report covering the first period of training, he explained that the change from a camera mounted on an empty spectacle frame to a hand-held camera with a zoom lens forced him to lose 'vestibular feedback', but allowed him to scan the whole object instead of parts of it. In the second period, the main issue was performing mobility tasks with two new versions of the TVSS built in the back of a wheelchair and a matrix of

[1] A Google Scholar search yielded 4290 hits in his ten most cited works. Search performed on March 28, 2017.

actuators placed on the abdomen. What is interesting in both cases is the relevance of the exploratory behavior: "I was surprised at how rapidly my ability to scan returned. This skill was the most important I had to reacquire because without it I could not recognize anything." In a review article, Bach-y-Rita (1983) recognized the importance of the exploration and the contingent information as well:

> Facility in directing the camera was accompanied by a change in the sensation derived from the patterned punctate stimulation of the skin. In the early stages of training (or when the camera was either immobile or under the control of another person), the subjects reported experiences in terms of the sensations on the area of skin receiving the stimuli. However, when they could easily direct the camera at will, their reports were in terms of objects localized externally in space in front of them. The provision of a *motor linkage (camera movement) for the sensory receptor surface on the skin produced a surrogate 'perceptual organ'.* [emphasis added] (Bach-y-Rita, 1983, p. 30)

Although Guarniero was not confident with the possibilities of the TVSS, Jansson (1983) started a project for navigation using that device. Jansson did not report detailed measures, but he stated that it was possible to perform a slalom walking in an area of 2 meters wearing a portable version of the TVSS with a matrix of 32 x 32 electrodes on the abdomen. However, he reported that the stimulation for pointing at the target was nearly painful. Interestingly, he commented that previous studies made with the haptic version of the elektroftalm (Starkiewicz & Kuliszewski, 1963 , spelled 'electrophthalm' in Jansson's article) were successful to guide participants in an area of six meters.

2.1.2 The Expansion of Sensory Substitution

Since those pioneering studies, a substantial number of SSDs has been built. Although it is almost impossible to describe all those devices, reviews of popular auditory and haptic SSDs can be found in Dakopoulos and Bourbakis (2010), Jones and Sarter (2008), Liu, Liu, Xu, and Jin (2010), and Visell (2009). In this dissertation, I am going to delve into visual-to-tactile substitution more than visual-to-auditory substitution. This is so because blind people prefer information that does not interfere with their auditory system. Normally, they take advantage of the hearing modality to compensate the loss of vision that is primarily used for distant events.

Besides this reason, Lenay et al. (2003) gave two more motives to use touch for sensory substitution. First, they argued that haptic substitution rather than auditory substitution is discrete in terms of the actual information received by the user. This is easily understandable: the person wearing a vibrotactile device is the only one that can perceive a vibration. Meanwhile, the sound of an auditory device could be perceived by other people if earphones are not used. As mentioned above, interferences with the hearing modality may be problematic, and it can easily be understood why earphones are not a satisfactory solution for visually-impaired people. Then, discretion is rarely assured with auditory SSDs. The other advantage of touch over audition commented in Lenay et al. (2003) is that "stimulation of the cellular receptors which contribute to the sense of touch make it possible to transmit information in parallel to the central nervous system." In fact, Lenay and colleagues highlighted that this parallelism can be leveraged to perceive resolutions superior to those material resolutions of a matrix of tactors by establishing a sensorimotor coupling. This phenomenon is known as 'hyperacuity' and it is exemplified in Chapter 5, page 128.

However, haptic substitution has several disadvantages too. On one side, vibrotactile devices have more technological difficulties than auditory devices (Lenay et al., 2003), for example, regarding battery supply. On the other side, haptic devices need to be eventually attached to the user, which can be annoying —especially under warm conditions. A range of researchers, then, have centered on the development of auditory devices instead of haptic devices. The former devices offer encouraging results regarding sensory substitution (Auvray, Hanneton, Lenay, & O'Regan, 2005; Bermejo, Di Paolo, Hüg, & Arias, 2015; Striem-Amit, Guendelman, & Amedi, 2012). Among the broad group of SSDs, three auditory SSDs are considerably cited in this dissertation and a brief review of them is provided. The rest of the commented SSDs are haptic devices. The list provided in the following section is not exhaustive as it is almost impossible to track all devices that have been reported in experiments and patents. Instead, it intends to summarize the key features of a group of devices that are relevant for this dissertation.

2.1.3 Review of SSDs

Auditory SSDs

'NavBelt' (Borenstein, 1990): This device was conceived to guide users through sounds in spatial navigation but regardless of user exploration. The technology is a mixture of ultrasonic sensors placed around the abdomen with a belt and robot-based technology for obstacle avoidance and path selection (Borenstein, 1990; Shoval et al., 2003). The sound is transmitted through earphones. This device shows some problems with the absence of distance-related information and interferences with the white cane. It seems that it is not possible to inform users about the presence of obstacles with time to change the path and avoid obstacles.

'The vOICe' (Meijer, 1992): This device consists of a camera that convert images into a grey-scale picture that it is scanned from left to right (Auvray, Hanneton, & O'Regan, 2007). Then, it transforms the brightness of each pixel in a sound that can be heard with earphones or headphones. The emitted frequencies are a function of the position of the pixels regarding height. The amplitude of the sinusoid is a function of the brightness for each pixel. In sum, the y-coordinate of pixels and their brightness are used to obtain a complex sound that varies in time following the x-coordinate of the image.

'The Vibe' (Durette et al., 2008): This is a device that converts video to sounds similarly as The vOICe does. The pixels are first grouped in 200 receptive fields dividing the image, and then a sound is linked to each receptive field. The frequency of each sound is a function of the position of the receptive field center in the y-coordinate. The interaural loudness is a function of the position of the receptive field center in the x-coordinate. The delivered sound is the sum of sounds of each receptive field and it is transmitted via headphones.

Tactile SSDs

'Ultracane' (EU Patent No 98957007.2, 1998): This device consists of a white cane with a sonar at the end. It produces vibrotactile signals when an obstacle is placed within a detectable range of the sonar (from 3 to 4 m as described in the original patent; from 2 to 4 m in the settings reported in Sound Foresight Technology, 2011). The vibration can be felt using two buttons on the handle, where the thumb is grasping the cane. Although interesting non-scientific communications have been reported using this device, there is little experimental evidence and no comparisons with other devices. However, visually-impaired people can access to use it since it is marketed in the United Kingdom.

'Tongue Display Unit' (TDU; US Patent No 6430450 B1, 1999): This display is the second project of a haptic device carried out by Bach-y-Rita and colleagues after the TVSS. It was also identified with the name of BrainPort for the similarities that these authors found with a USB port in a computer (Bach-y-Rita & Kercel, 2003). The device includes a matrix of 12 × 12 electrodes placed inside the mouth. The rest of the device is similar to the TVSS: it includes a camera that picks up a 2D image and a controller that transforms the brightness of each pixel into an electrotactile pulse that is sent to the corresponding electrode in the matrix.

'Guidecane' (Shoval et al., 2003): This second development of Borenstein and colleagues intended to solve the problem of the Navbelt with 2-D images. One intuitive definition provided by the authors identified the Guidecane with a robotic guide dog. This device is a cane with wheels at the end that turn based on the instructions sent by a controller. The user indicates the heading direction with a joystick and the sonar detects if there is any obstacle that needs to be avoided.

'Haptic Glove' (Zelek, Bromley, Asmar, & Thompson, 2003): This project aimed to develop a haptic device for obstacle avoidance that could be used in combination with other assistive devices or mobility aids. The device consists of a glove worn on the left hand with a set of vibrotactile actuators attached to the glove, a camera that is placed on the chest, and a laptop that uses a stereovision algorithm to provide information about obstacles. When an obstacle is closer than the established threshold, the actuator related to the direction of the obstacle is activated. For example, in. Zelek et al. (2003), three directions were used: left, front, and right; each one related to a different finger: fifth, second and first finger, respectively. In a previous technical report made by Zelek and colleagues, they added two directions by dividing left and right directions into 'a little' or 'more' left and right directions (Zelek, Audette, Balthazaar, & Dunk, 2000), although this seems unused afterwards.

‘Vibrotactile waist belt’ (van Erp, van Veen, Jansen, & Dobbins, 2005): This device includes a minicomputer, a digital compass, batteries and a GPS receiver inside a backpack and a haptic display that is placed on the waist. This display is an elastic band with 8 vibrotactile actuators distributed along the band every 45º. The intensity of vibration is fixed, and the vibration rhythm (i.e., the time span of the pulses) depends on the distance to the next waypoint. The direction of the next waypoint is indicated by the vibration of the corresponding tactors inside the belt, which is activated if the waypoint direction is included in the ‘sensitivity’ range of 45º that has each tactor.

‘FeelSpace Belt’ (Nagel, Carl, Kringe, Märtin, & König, 2005). Although the substitution in this device could be controversial, I find it useful to describe the functioning of a unique device that provides information of the north direction using vibrotactile stimulation. Briefly, the device consists of a set of 12 vibrotactile actuators attached to a belt, a controller, and a compass. The north is indicated with continuous vibration of the vibrotactile actuator that points in that direction. This project was directed to test the new modality hypothesis based on the establishment of new sensorimotor contingencies.

‘EPFL project’ (Cardin, Thalmann, & Vexo, 2007). This device has four sonar sensors, eight vibrotactile actuators placed around the body from one shoulder to the other, a microcontroller, and a PDA (Personal Digital Assistant). If one of the sensors detects an obstacle (or two sensors given that they are a bit overlapped), the corresponding actuator(s) located in the same part of the body is (are) activated. The vibration is a burst of 200 ms updated each second with an intensity proportional to the distance between obstacle and user.

‘Visual-to-tactile photodiode device’ (Siegle & Warren, 2010). This minimalist device consists of a photodiode attached to the index finger, a computer, and a vibrotactile actuator placed in the center of the back of user’s seat. The intensity of light measured by the photodiode is transformed into a voltage level that activates the actuator whenever a given threshold is surpassed.

‘Sensory Augmentation Glove’ (Carton & Dunne, 2013). Although the authors designed this device for firefighters who work in low-vision conditions, its features make it a noticeable device for vision substitution in general. The glove has a microcontroller, a sonar, and two motors on the dorsal side, one near the base of the middle finger and the other next to the wrist. The sonar detects the distance to surfaces that is used to determine the intensity of vibration of the two motors attached to the glove.

'CAYLAR' (Faugloire & Lejeune, 2014): Similarly to the vibrotactile waist belt (van Erp et al., 2005), this device has eight tactors distributed along the waist of a user. The tactors are wired independently, which allows a better adaptation to the user's shape than the elastic band of van Erp and colleagues. This also means a higher precision in placing the tactors on the body with a separation of 45º between them. The user wears a receiver of a tracking system that is used to deliver the information about orientation.

The previous list describes several of the most widely-known SSDs built during the last 30 years of research in the field. When one observes the great diversity of SSDs built to substitute vision, one thing that quickly comes to one's mind is the absence of these devices in everyday life. Despite the great expectations produced in the seventies with new devices, the use of SSDs by visually-impaired people is still low (Spence, 2014). Several devices, like the TVSS, count with a high number of experiments testing their features. Even so, it is almost impossible to encounter these devices outside a laboratory. Although SSDs have been useful in basic research discussing problems such as distal attribution, information contingent to action, or amodal processing, authors like Dakopoulos and Bourbakis (2010) emphasized the need of visually-impaired people to have a reliable, robust system to reach the level of confidence to really use these devices. These authors mentioned several features to improve the design of haptic SSDs:

> 1) Free-hands: not requiring from the user to hold them. Remember that the users will still hold the white cane, the most undisputable travel aid; 2) Free-ears: despite the advantages of echolocation, spatial sound, and similar techniques, the user's ability to listen environmental should not be interfered; 3) Wearable: it offers flexibility to the users and using the advantages of wearable technologies; 4) Simple: easy to use (operation and interface not loaded with unnecessary features) and without the need of an extensive training period. (Dakopoulos & Bourbakis, 2010, p. 35)

Dakopoulos and Bourbakis (2010) also indicated that the challenge is how and what information is sent to the user. It seems reasonable to think that an account like ecological psychology can be useful, above all, regarding this last feature. Reasons for that assertion are provided in the next section.

2.2 Ecological Psychology

Ecological psychology is an antirepresentational approach[2] that challenges mainstream explanations of cognition defended by cognitivism and behaviorism. The horizon of the empirical work in ecological psychology is the description of lawful relations in the organism-environment system (O-E system) (Travieso & Jacobs, 2009). Traditional approaches in cognitive science depict perception as the result of a linear operation on the stimulus, which is transformed in a representation of the original information to be useful for the human mind. The cognitive processes occur between the sensation provoked by the stimulus and the response executed by the action system. The capable algorithms of this change correspond with the second level of description in Marr's words (1982, p. 25). Ecological psychology offers a different view about perception and, extensively, about cognition. The ecological approach is an embodied, embedded, antirepresentational, and biosemiotic account that intends to explain cognition from a bottom-up approach (Heras-Escribano, 2015). Among the differences that can be found between cognitivism and ecological psychology, here I mention the most relevant ones for this dissertation: the perception-action loop, the concept of affordances, the notion of specificity, and direct learning.

2.2.1 Perception-Action Loop

This concept refers to the idea that perceiving is acting, and acting is perceiving, because these processes are conjoint and reciprocal. They are both sides of the same coin. As Richardson, Shockley, Fajen, Riley, and Turvey (2008) claimed, the ecological approach does not support any separation between perception and action:

[2]This account is usually described as a naturalized first-person perspective different from certain interpretations of the enactive account and the sensorimotor approach which have been related to a structural mechanicism, see for example Ibáñez-Gijón (2014).

> On arguing that perception and action are cyclic, the ecological approach is not simply stating that perception and action influence or interact with each other (...), but that perception and action are of the same logical kind, and are mutual, reciprocal, and symmetrically constraining (Shaw & Turvey, 1980). (Richardson et al., 2008, p. 174)

The notion of a perception-action coupling can be found since the very beginning of ecological psychology. Gibson (1966) explained that, contrary to a passive conception of the human senses, we should consider them as perceptual systems because they entail more than simply stimulation from the environment:

> The classical concept of a sense organ is of a passive receiver, and it is called receptor. But the eyes, ears, nose, mouth, and skin are in fact mobile, exploratory, orienting. Their input to the nervous system will normally have a component produced by their own activity. (Gibson, 1966, p. 33)

This conception of perception is radically different from the notion of perception in the classic, cognitivist view. This idea, which is also the backbone of other antirepresentational approaches, can be traced back to authors like Dewey (Aivar, Fernández, & Sánchez, 2002). In his work on the 'The Reflex Arc Concept in Psychology', Dewey (1896), pointed out:

> Upon analysis, we find that we begin not with a sensory stimulus, but with a sensori-motor coordination, the optical-ocular, and that in a certain sense it is the movement which is primary, and the sensation which is secondary, the movement of body, head and eye muscles determining the quality of what is experienced. (Dewey, 1896, pp. 358-359)

Turvey (2004) described the perception-action cycle as a Möbius band, opposed to the conception of input-process-output scheme. In the literature about sensory substitution, perception is mostly understood in a way that was criticized by Dewey (1896); that is, a reflex arc: a user of a SSD is provided with a stimuli, then a lot of inner processing takes place, and then an action in executed. On the contrary, ecological psychology claims that changes in the perception-action loop (e.g., the achievement of bipedal locomotion in infants) brings new possibilities for action (e.g., the possibility of carrying objects) related to different detected information that is, the perception of new affordances (Gibson, 1988).

2.2.2 Affordances

This key term was coined by Gibson (1966, p. 285) to provide an alternative of the term 'value' as it is used in philosophy. In 1979, Gibson published 'The Ecological Approach to Visual Perception' where he offered a more detailed view on affordances. Gibson defended in his book that affordances were the objects of perception. They are the possibilities for action in an organism-environment system. The set of affordances that exist in an organism-environment system is a niche, a broader concept than the habitat because "a niche refers more to how an animal lives than to where it lives" (Gibson, 1966, p. 128). Then, an organism embedded in her system knows her environment because she perceives affordances, which are the epistemic connections between the agent and the environment. In Richardson and colleagues' (2008) words:

> ...affordances are perceived by detecting lawfully structured information ...that invariantly specifies features (capabilities) of a particular perceiving–acting agent in relation to features of a particular substance, surface, object, or event. A water surface with adequate tension can afford locomotion for an insect but not a human. (Richardson et al., 2008, p. 179)

The idea behind this is that affordances are properties in the organism-environment system that cannot exist outside this system. Thus, the objective-subjective and organism-environment dichotomies are false divisions for ecological realism. Being true that the discussion about the ontology of affordances is an open debate (see, for example, Chemero, 2009; Heras-Escribano & de Pinedo, 2016; Warren, 1984), all authors within the ecological approach defend that they are directly perceived.

2.2.3 Specificity

In the above-mentioned quotation of Richardson et al. (2008), the word 'specifies' appears in relation to invariant features. The concept of specificity belongs to the core concepts of ecological psychology as this is the way to explain how, from the detection of information, we can perceive affordances. A canonical example to explain specificity is dynamic touch, a perceptual subsystem which has such a research tradition that an experimental paradigm has been named with the same term (an example of this use can be seen in Withagen & Michaels, 2004; the research tradition is shown in Turvey, 1996). Imagine a participant in an experiment who holds a rod from one end. The rod and the hand are hidden behind a curtain that occludes vision from the participant's perspective. The experimenter asks the participant if she can indicate the length of the rod (pushing a platform to its corresponding place or moving a strip to measure a space, for example). The participant wields the rod and moves the measurement system to the point in which she perceives the end of the rod.

The information that its accesible for participants in dynamic touch experiments is related to the rotational inertia as it is not possibe to change the way of grasping the rod or view it. Different experiments have shown that, among the three candidates (all moments of mass distribution, i.e., mass, static moment, and moment of inertia) that could be theoretically used, the moment of inertia seems to be used to perceive the rod's length (Cabe, 2010; Pagano & Cabe, 2003; Solomon & Turvey, 1988). But, when the moment of inertia is not available due, let's say, to restricted movement, then, the static moment or the mass have to be used and judgements are less similar to the rod's actual length (Lobo & Travieso, 2012). In the dynamic touch literature, the superiority of the moment of inertia is explained because it has a one-to-one relation with the reachability of the rod; that is, this invariant is specific. The same rationale about specificity has been successfully applied to the relative mass of colliding balls, for example (Jacobs, Michaels, & Runeson, 2000).

A very interesting way of using this term was offered by Käufer and Chemero (2015, p. 157). While explaining the use of the word 'specify' in the ecological context, they claimed that its meaning is similar to the one used in legal contracts; that is, as a guarantee for the presence of certain elements (for example, a certain pattern of light guarantees a surface).

2.2.4 Direct Learning

Strelow (1985) noted an interesting problem for explaining perceptual learning from an ecological approach:

> Gibson (1966, 1979) referred to perceptual activity as an active searching process, and perceptual learning as an education of attention. However, without an explanation of what controls the selective process, this assumes rather than explains selectivity and intentionality (Fodor & Pylyshyn, 1981). (Strelow, 1985, p. 244)

In recent years, this problem seems overcome thanks to the direct learning theory (Jacobs & Michaels, 2007) that explains the way in which we move from one invariant to another. In this perceptual-motor theory, direct learning is defined by the (informationally-guided) education of attention to detect more useful information presented as a low-dimensional manifold (Michaels et al., 2008). The difference with the concept of education of attention that can be found in Gibson (1966) lies in the mathematical apparatus that let us observe the direct character of learning represented by a path in the manifold. This path is constrained by the vector field which represents the discrepancies between judgements (actions) and feedback (outcomes), that is, convergence information that guides learning, Then, improvements in performance can be explained without the need to propose an indirect process in perceptual-motor learning (Jacobs & Michaels, 2007; Michaels et al., 2008). The specificity of invariants is related to the above-mentioned discrepancies; in other words, the convergence information (directly) pushes the agent to move from non-specific invariants to (more) specific invariants, and this explains those improvements in performance. With that being said, there is neither a homunculus nor an inner controller in charge of the learning proccess: Thus, the direct character of learning is preserved (Jacobs & Michaels, 2007).

2.3 An Ecological Sensory Substitution

In this section, my proposal is to approach sensory substitution from an ecological perspective, taking into account what has been shown in Sections 2.1 and 2.2. To date, just a few studies using SSDs make an explicit mention to the ecological approach in the design of devices and/or in experiments carried out with them. In this section, I pay attention to those studies describing in which sense the ecological approach has been implemented.

'CyARM' (Cyber Arm, Ito et al., 2005: This is a light device inspired by Runeson's (1977) description of 'a smart mechanism' like the polar planimeter. It is equipped with a sonar, a controller, and a motor with a rolled wire. This wire is connected to the device at one end and to the user at the other end. When there is an object within the range of the sensor, the motor is activated, the wire is rolled up, and the tensile strength of the wire increases. On the contrary, when the distance between user and object increases, the motor releases the rolled wire, and the wire's tensile strength decreases. One of the advantages of this system is the continuous adjustment between the distance measured by the sonar and the tension of the wire. This avoids codification of messages. Ito and colleagues claimed that the contingency they used was very intuitive and the update frequency (20 Hz) sufficient to be useful in simple tasks, like, for example, either determining the presence/absence of a big object (2×1 m) or finding gaps between objects.

A second version of this device is described in Akita, Komatsu, Ito, Ono, and Okamoto (2009). The CyARM was lighter in this version and a complete experiment on distance perception of big objects was conducted. Results showed a high correlation ($r = .87$) between perceived distance and actual distance. Nevertheless, a few issues concerning this device can be raised: First, navigation tasks using this new version were not reported even though the authors claimed that the device was designed to be an electronic travel aid for the blind. Second, the necessary physical connection with the wire prevents users to move their arm and trunk, which can be problematic in everyday life. And third, the resolution of the ultrasonic sensor must be improved given that the original one did not allow a fine measurement of distance (see Ito et al., 2005, to follow author's discussion regarding the second and third points).

'Future-Body Finger' (FB-finger, Ito et al., 2012): This is the second device developed by Ito and colleagues. In this hand-held device, users rest the index finger on a cantilever that moves in an angle that is a function of the distance to an object. Apart from the ecological approach, the authors claimed that the device enable people to have an 'extended mind experience'; that is, they make use of information in the environment through this device to extend cognition beyond the skin's limits in a similar way that Clark and Chalmers (1998) claimed in their article. Although it is not clear whether the extended mind concept has something to add to the organism-environment system defended by Gibson, these authors considered that the FB-Finger is a step toward the 'Extended Body' and, therefore, to improve quality of life. Two major changes were made regarding the CyARM. First, the measurement of distance is made with two infrared sensors and a sonar while a fourth sensor measures the intensity of light. The controller transforms measured distance into movement of a servo motor which controls the cantilever that changes the angle of the index finger as a function of this distance; that is, the angle of the joint decreases when the distance to objects increases and, conversely, the angle of the joint increases when the distance to objects decreases.

'Enactive Torch' (Froese, McGann, Bigge, Spiers, & Seth, 2012): This device has an infrared sensor that measures the distance to first-encountered objects. It has one vibrotactile actuator that can be attached to the wrist, a microcontroller, and a battery power. The microcontroller transform the distance measured with the infrared sensor into a voltage level that is transmitted to the vibrotactile actuator with intensity inversely proportional to the distance measured by the sensor.

This device has been tested in an experiment based on the ecological approach and the affordance known as pass-through-ability (Favela, Riley, Shockley, & Chemero, 2014). In this experiment participants made affordance judgments in different conditions. Participants had to report whether they thought that they could walk through a given aperture without altering their normal gait, that is, without making movements trying to fit into the aperture. Three groups were compared: a first group in which participants used vision, a second group in which participants used a cane while they were blindfolded, and a third group in which blindfolded participants used the Enactive Torch. After scaling the aperture sizes with the actual ability of passing through for each participant, the point of 50% of correct responses or point of subjective equality (PSE, estimated with a logistic function) was compared for participants in each group. The ANOVA performed on the PSE did not show differences among performance conditions. The authors concluded that the Enactive Torch is useful to perceive the pass-through-ability affordance and, therefore, that new directions in the design of devices for the blind should be investigated.

'Tactile-Sight' (TSIGHT, Cancar, Díaz, Barrientos, Travieso, & Jacobs, 2013): This device was developed by the Perception and Action Research Group (UAM) in collaboration with the Robotics and Cybernetics Research Group (UPM). This device consists of a haptic display with vibrotactile actuators attached to an elastic band that is placed in the abdominal area, a Kinect camera placed on the chest, a power module, and a control module placed inside a backpack. The image, picked up by the camera, is divided into 12 $\times$ 6 sections in which the distance to the first-encountered surface is measured. The microcontroller transforms those distances into voltage levels that activate the corresponding vibrotactile actuators. The intensity of vibration increases when distance to surface decreases and, conversely, the intensity of vibration decreases when distance to surface increases as, for example, in Cardin et al. (2007).

Exploratory behavior has a prominent role in the use of this device according to the ecological approach. A previous publication of Díaz, Barrientos, Jacobs, and Travieso (2012) already showed the importance of the perception-action loop in an experiment where participants had to detect the presence of a platform using a haptic SSD. One of the groups of participants who performed the Experiment 3 of this paper (the self-yoked group) used the vibrotactile flow that was recorded in a previous session by the same participants, while the other group actively moved to perceive the platform in a dynamic condition. The self-yoked group had a worse performance than the dynamic group, which was interpreted by the authors as evidence in favor of including exploration in sensory substitution.

The TSIGHT was designed having this experiment into account and, instead of focusing only on the stimulation, it allows users to explore the environment and receive information contingent on that exploration (i.e., to engage in a perception-action loop). The high versatility of this device allows the study of task-specific information and its portability allows users to move freely in large exploration areas. In an experiment reported by Cancar et al. (2013), the experimenters asked participants to judge the time to contact of an approaching ball projected on a screen using either vision, the TSIGHT, or both (i.e., crossmodal condition). When the size of the ball was small, a few number of actuators were activated. This number increased when ball became bigger and, consequently, the contact was imminent. The two types of information, that is, visual and vibrotactile, stopped a few moments before the impact to allow actual estimation of time to contact. No significant differences between conditions were found. This outcome can be interpreted as evidence for the usefulness of expansion in haptic devices. In a real-environment test, the experimenters threw a ball to participants wearing the TSIGHT and they reported that in 7.1 of 10 trials participants correctly hit the ball to avoid the impact (Cancar et al., 2013).

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Chapter 3

Stepping on Obstacles with a SSD on the Lower Leg

Practice[1] is essential for an adapted use of sensory substitution devices. Understanding the learning process is therefore a fundamental issue in this field of research. This study presents a novel sensory substitution device worn on the lower leg and uses the device to study learning. The device includes 32 vibrotactile actuators that each vibrate as a function of the distance to the nearest surface in a particular direction. Participants wearing the device were asked to approach an object and to step on the object. Two 144-trial practice conditions were compared in a pretest-practice-posttest design. Participants in the first condition practiced with vibrotactile stimulation while blindfolded. Participants in the second condition practiced with vibrotactile stimulation along with normal vision. Performance was relatively successful, both types of practice led to improvements in performance, and practice without vision led to a larger reduction in the number of errors than practice with vision. These results indicate that distance-based sensory substitution is promising in addition to the more traditional light-intensity-based sensory substitution and that providing appropriate sensorimotor couplings is more important than applying the stimulation to highly sensitive body parts. The observed advantage of practice without vision over practice with vision is interpreted in terms of the guidance hypothesis of feedback and learning.

[1]This chapter is published with the next reference: Lobo, L., Travieso, D., Barrientos, A., & Jacobs, D. M. (2014). Stepping on obstacles with a sensory substitution device on the lower leg: Practice without vision is more beneficial than practice with vision. *PLoS ONE, 9*(6), 1–10. doi:10.1371/journal.pone.0098801

3.1 Introduction

Sensory substitution devices are devices that transform ambient energy patterns typically associated to one sense modality into patterns that can be detected through another modality. Commonly used transformations are visual to auditory and visual to tactile. Sensory substitution devices raise important fundamental scientific questions, including questions related to brain plasticity (Bach-y-Rita & Kercel, 2003) and sensorimotor theories (O'Regan & Noë, 2001). The majority of the applications of sensory substitution devices are directed to visually impaired people (Dakopoulos & Bourbakis, 2010), but other applications can be found in fields such as pilot navigation, balance control, speech comprehension, and other fields (Jones & Sarter, 2008).

Some type of training with sensory substitution devices is beneficial or even necessary (Guarniero, 1974, 1977; Jansson, 1983). Lenay et al. (2003), for example, argued that "even the most user-friendly device will inevitably require a substantial learning process" (p. 286). These authors further claimed that the availability of appropriate learning protocols is a crucial factor for the success of sensory substitution devices. In line with such claims, the main purpose of the here-reported experiment is to contribute to the understanding of learning with sensory substitution devices. In addition to noting the importance of learning, Lenay and colleagues elegantly expressed several theoretical observations that are important for the design of sensory substitution devices, some of which are related to the ecological approach to perception (Gibson, 1979).

From the ecological point of view, perception is the picking up of higher-order variables that are useful for goal-directed behavior. To give a few examples, often-studied higher-order variables include the focus of expansion of the optic flow as specification of the direction of movement, or texture gradients as specification of terrain orientation. The ecological approach considers perception and action as two sides of the same coin; both are part of a unique process of information detection. A large number of empirical studies support the role of exploratory movements in the detection of information. Prominent among these studies are the bodies of work on dynamic touch (Turvey, 1996) and on the concept of exploratory procedures (Lederman & Klatzky, 1987). Given the importance of exploratory movements in the regular functioning of perceptual and perceptual-motor systems, it seems reasonable to expect that, in order to be effective, sensory substitution systems should allow exploratory movements and sensorimotor couplings, and thereby the detection of environmental information specific to action-relevant properties.

Inspired by the ecological framework, we have previously designed and constructed sensory substitution devices that transform distance-related information into vibrotactile patterns on the torso. We experimented with these devices using tasks that are among those most typically considered by proponents of the ecological approach: the perception of obstacles (Díaz et al., 2012) and of time to contact (Cancar, Díaz, Barrientos, Travieso, & Jacobs, 2013). The here-presented research continues this overall approach to sensory substitution. We designed a novel device that tranforms distance-related information into vibrotactile patterns on the lower leg. An experiment is reported in which participants use the novel device to step on ground-level obstacles. The purpose of the experiment is to respond to learning-related questions.

One of the first systematic investigations of learning in sensory substitution was performed with a device referred to as the binaural sensory aid (Warren & Strelow, 1984). This device associates the distance of a target to a pitch, and the direction to an interaural amplitude difference. In the experiment reported in Warren and Strelow (1984), the perception of distance and direction with the device improved after a training phase in which users received haptic feedback by touching the targets. Learning effects have also been reported in Epstein, Hughes, Schneider, and Bach-y-Rita (1989) and Kim and Zatorre (2008). In Epstein et al. (1989), the authors used vibrotactile stimulation applied to the left index finger of participants with an Optacon and observed learning in the absence of feedback. In Kim and Zatorre (2008), a visual-to-auditory device, referred to as *the vOICe* (Meijer, 1992), was used and visual feedback was provided without motor interaction with the environment. In addition to these and other studies with laboratory tasks, learning effects have been reported after practice with more dynamic and arguably more natural interactions with objects (Auvray et al., 2007) and after the prolonged and continuous use of substitution devices outside the laboratory (Nagel et al., 2005; Proulx, Stoerig, Ludowig, & Knoll, 2008).

In comparison to the large number of studies that demonstrate that learning occurs with different devices, different tasks, and with different types of feedback as well as without feedback few studies focus on factors that may facilitate or impair learning. Consider the following question: In learning to use a device that provides vibrotactile stimulation, what are the effects, if any, of the absence of vision during practice as compared to the possibility to rely on vision during practice? Proulx et al. (2008) tested performance with a sensory substitution device (the vOICe) that was used during 21 days, either with or without vision. Their study, however, included only one participant in each of these conditions (as well as more participants in conditions that are not described here). Also relevant is an experiment reported in Segond, Weiss, and Sampaio (2005), in which participants learned to control a robot on the basis of tactile stimulation coupled to a camera placed on the robot. The experiment included practice phases with visual and tactile stimulation as well as practice phases with tactile stimulation only. Even so, because the purpose of the experiment was not to compare the different practice phases, all participants went through the phases in the same order, making an unbiased comparison impossible. Hence, more research is needed to understand the effects of the presence or absence of vision while learning to use non-visual sensory substitution devices.

To perform such research and to advance our broader research project, we constructed a sensory substitution device with 32 actuators on the frontal part of the lower leg. If a user stands straight up on a flat ground surface without obstacles, then all actuators vibrate with a (low) standard vibration. Deviations from this situation—which may be due to movement of the user or to the presence of an obstacle—lead to changes in the pattern of vibration. Each actuator vibrates as a function of the distance to the nearest surface in a particular sensing direction: the closer the nearest surface, the more intense the vibration. The so-computed patterns of vibration and the changes therein may allow users to perceive ground-level obstacles and to step on them. Our device does not include real sensors. Instead, to control the vibration of the actuators, the position of the lower leg is detected with movement registration cameras, and the distance to the nearest surface (either the floor or a box) is computed on-line on the basis of knowledge about the locations of the surfaces in the environment. In the reported experiment, participants wearing the device were asked to walk toward objects and to step on them.

In accordance with the issues raised above, the aims of our study are (a) to determine if it is possible to use our device to step on ground-level obstacles and, thereby, to confirm the usefulness of this type of device, (b) to determine if and how the execution of this perception-action task changes and improves with experience with the device, and (c) to determine if different practice conditions have different effects on performance. To test the effect of experience, we used a pretest-practice-posttest design with four 36-trial practice blocks. A first group of participants performed the practice blocks while blindfolded whereas a second group performed the practice blocks with vision.

Our analyses address the time needed to perform the task and several error measures: the number of trials on which the foot is lifted before reaching the obstacle, the number of trials on which the foot is not lifted sufficiently so that the obstacle is hit, and the sum of these errors. Also analyzed are the distance (from the box) at which the foot is lifted and the maximum height of the lifts. A final measure concerns exploration. Displacement by walking implies continuous changes in the tilt of the lower leg (as well as of other body segments). With our sensory substitution device the tilt of the lower leg with the device may have an exploratory function in addition to its regular function related to displacement. This is so because the pattern of vibration is a function of the structure of the environment in combination with the position and orientation of the lower leg. As an indication of this exploratory function, we computed and analyzed the range of tilt of the lower leg at a moment at which one may expect to observe exploratory movements: just before the leg was lifted to step on the obstacle. We reasoned that a more pronounced exploration should be evidenced by a larger tilt range.

3.2 Method

3.2.1 Ethics Statement

This research project was approved by the committee for ethical research of the Universidad Autónoma de Madrid. Written informed consent was obtained from all participants.

3.2.2 Participants

Twenty students and faculty members (17 women, 3 men) participated in the experiment. Their mean age was 20.2 years (*SD*= 4.3). All participants were right footed. None of them had previous experience with this sensory substitution device. In return for their participation, the participants received book vouchers at the end of the last experimental session.

3.2.3 Apparatus

Figure 3.1 shows the set-up and an individual (in the case of the picture one of the authors) performing the task. The set-up included an approach area of approximately 2.00×0.50 m , six cardboard boxes of different heights (0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 m) placed at one of six possible distances from the participant's starting position (1.00, 1.15, 1.30, 1.45, 1.60, and 1.75 m), and a four-camera motion capture system (Qualisys Inc., Sweden). Figure 3.2 shows the part of the sensory substitution device that was worn on the leg. This part consisted of 32 actuators attached to the inner side of an adjustable elastic calf support. The actuators were coin-shaped motors (6.0×3.4 mm) that were placed in a zigzag line against the tibialis anterior muscle (parallel to the shinbone). As explained in the following paragraphs, the actuators vibrated as a function of the distance to the first-encountered object in a particular direction.

The four Qualisys cameras detected the position and orientation of two rigid bodies (each formed by four reflective markers) at a frequency of 100 Hz. One of the rigid bodies was attached to the right foot and the other one to the part of the device worn on the lower leg. The position and orientation of the rigid bodies were exported from the Qualisys software to MATLAB with the MATLAB plug-in of the Qualisys software. All on-line processing was done on a single PC (Intel Core i7, 3.07 GHz). The output of the on-line processing with MATLAB was an array of 32 driving voltages. These voltages changed with the participants' movements. The digitally-computed voltages were transformed into analog signals with two 16-channel digital/analog (D/A) conversion cards (NI-9264, National Instruments, Texas). The output of the D/A conversion cards was adjusted to the currents required by the actuators with two 16-channel printed circuit boards.

The on-line computations of the driving voltages were based on the positions and orientations of the actuators (derived from the measured position and orientation of the rigid body on the lower leg) in combination with predefined information

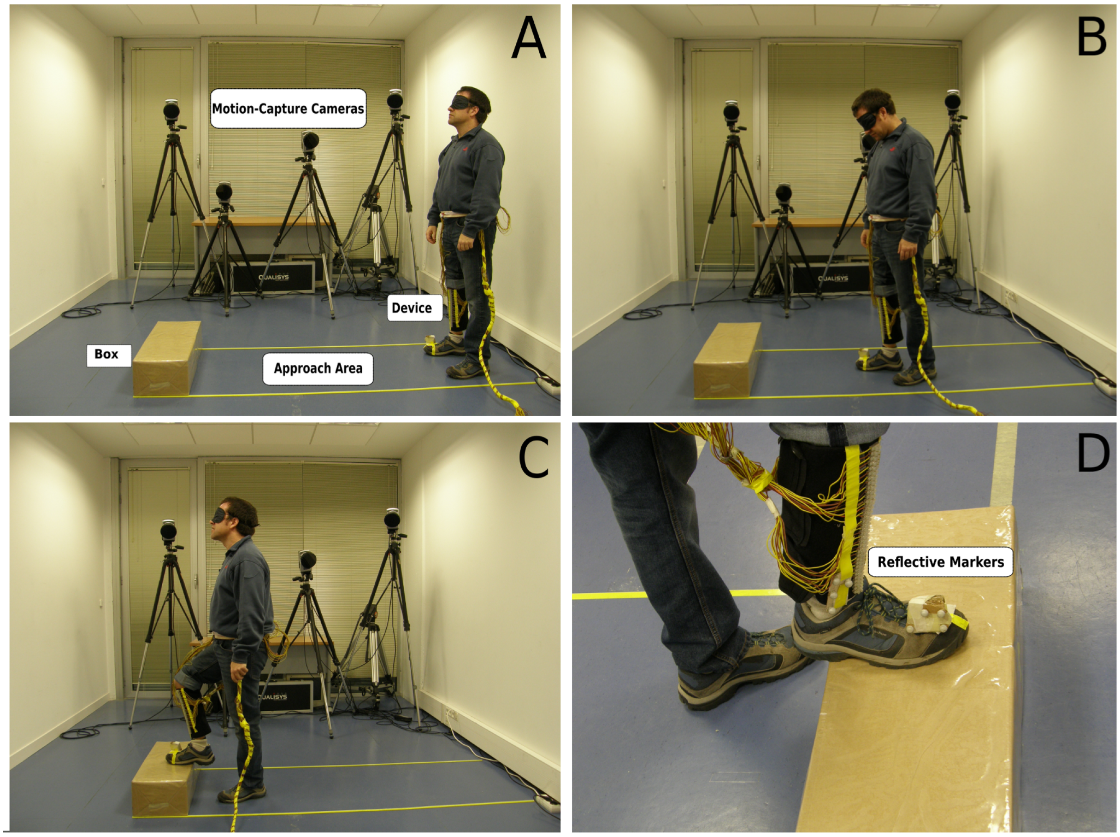

Figure 3.1: Experimental task and set-up. Participants walked through the approach area (Panels A and B) and aimed to step on the box (Panels C and D). Rigid bodies consisting of four reflective markers were attached to the right foot and to the lower right leg of the participant (Panel D). The position and orientation of these rigid bodies, and hence of the foot and the lower leg, were registered with four motion capture cameras. The experimenter was present during the execution of the task. Participants in the vision group were not blindfolded during training.

about the environment (the position and height of the box on a particular trial). In the on-line computations, each actuator was connected to a virtual (i.e., imaginary) sensor. At each moment in time, the driving voltage of the actuator was a function of the distance to the first-encountered object in the direction of the associated virtual sensor. We first describe the details of the distance-voltage relation for a single actuator and then present illustrative examples of patterns of vibration for the array of 32 actuators.

The upper left panel of Figure 3.3 shows the lower leg with a single actuator for a participant standing straight up in an environment without box. We refer to this situation as the standard situation. The dashed line shows the direction of the

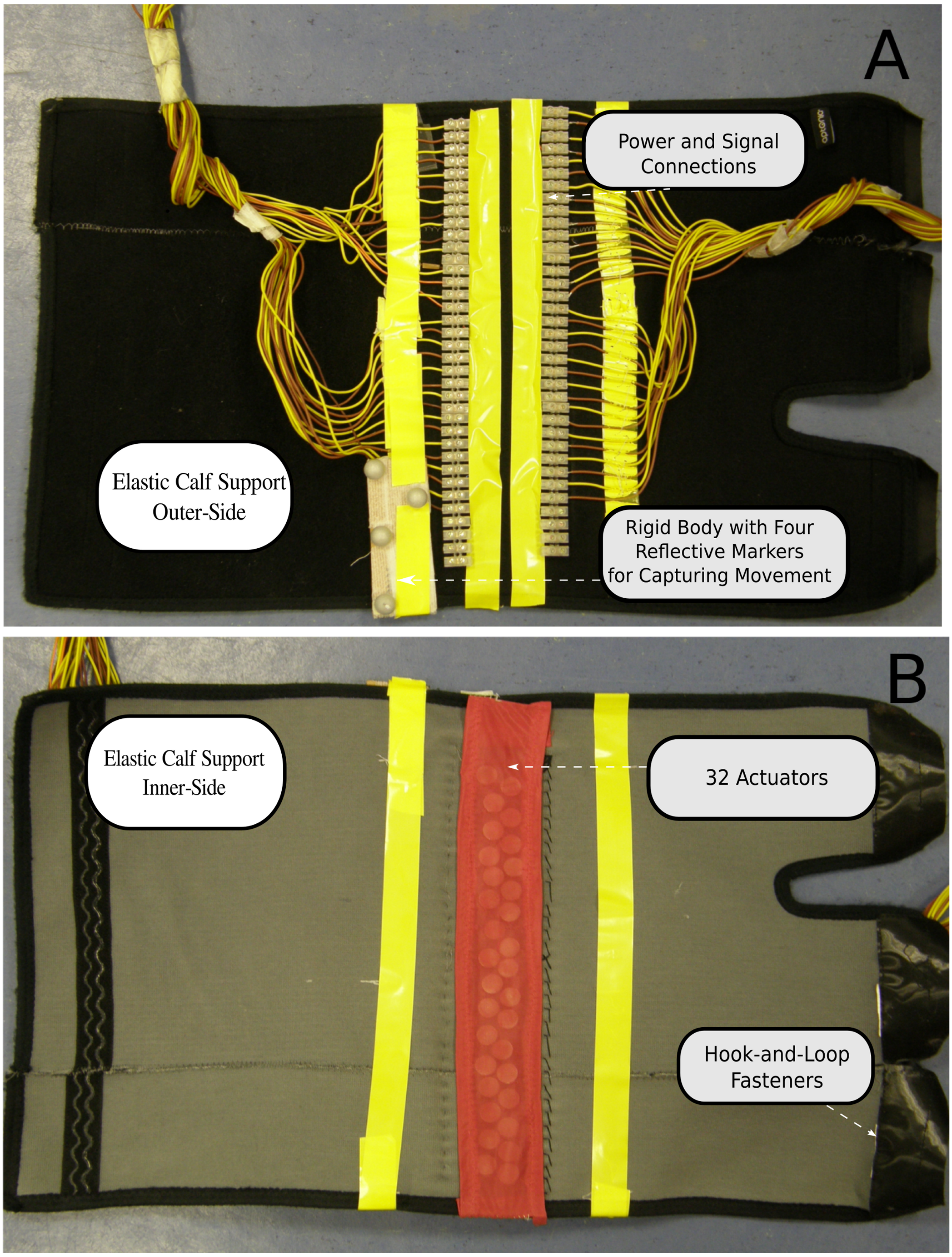

Figure 3.2: Part of the device worn on the lower right leg. The device included 32 vibrotactile actuators on the inner side of an elastic calf support. The actuators are visible in Panel B through the thin transparent fabric. A rigid body of four reflective markers was attached to the outer side of the calf support to register the position and orientation of the lower leg. Also attached to the outer side were the cables that provided power to the actuators on the inner side. The rigid body and the power cables are visible in Panel A.

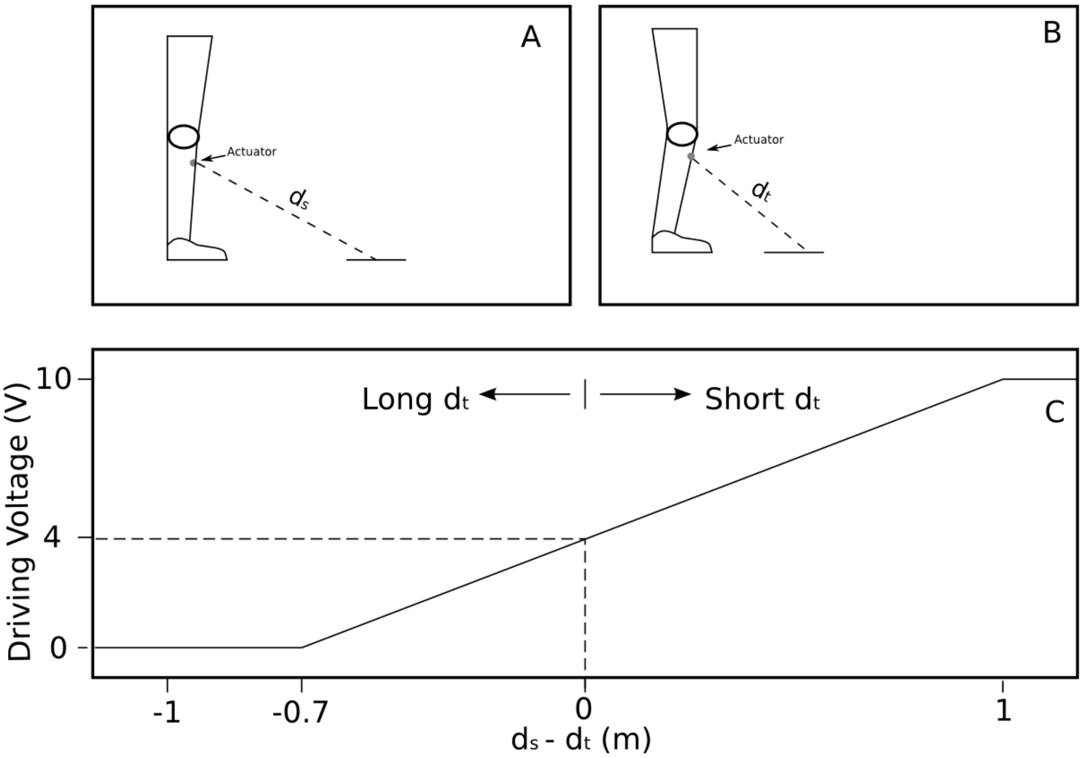

Figure 3.3: Single-actuator illustration of the distance-voltage relation. The upper left panel shows the lower leg of a participant in the standard situation with a single actuator. The dashed line indicates the direction of the virtual sensor and d_s indicates the distance between the actuator and the floor in that direction. The upper right panel shows the lower leg tilted forward, at a certain moment t; d_t indicates the distance between the actuator and the floor in the direction of the virtual sensor at moment t. The lower panel shows the digitally-computed driving voltage v_d as a function of d_s and d_t: the longer d_t with respect to d_s, the more negative $d_s - d_t$, and the lower v_d.

virtual sensor associated to the actuator. This direction was constant with respect to the lower leg even if the lower leg moved away from the standard situation. The distance between the considered actuator and the floor in the standard situation is indicated with the actuator specific value d_s (with d standing for distance and s for standard situation). The upper right panel shows a situation in which the lower leg has been tilted forward. In this situation the distance between the actuator and the floor in the direction of the virtual sensor, indicated by d_t (with t indicating that this is a time-specific distance), is shorter than d_s. The digital driving voltage, vd, was computed from the relation between the changing d_t and the constant d_s, using the following formula: $v_d = 4 + 6 \times (d_s - d_t)$. The lower panel of Figure 3.3

illustrates the dependence of v_d on $d_s - d_t$ defined by this formula. Note from the figure that the driving voltage of an actuator was 4 when $d_s - d_t = 0$ (e.g., in the standard situation). The driving voltage decreased linearly until its minimum of 0 for $d_s - d_t < 0$ and the driving voltage increased linearly until its maximum of 10 for $d_s - d_t > 0$ (i.e., when the actual distance was larger or smaller than the one in the standard situation, respectively).

To provide further intuitions about the functioning of the device, Figure 3.4 shows four patterns of vibration for the array of 32 actuators. The upper part of Figure 3.4A shows a participant standing straight up without being influenced by the box (i.e., a participant in the standard situation). Because, in such a situation, $d_t = d_s$ for each actuator, the driving voltage shown in the associated lower panel was 4 for each actuator. With the participant's movements, the 32 values for d_s remained constant but the values for d_t changed, giving rise to higher driving voltages for shorter distances (Figure 3.4B; participant leaning forward) and lower driving voltages for longer distances (Figure 3.4C; participant leaning backward). The presence of a box in the scanning area also affected the vibrotactile pattern (Figure 3.4D).

The directions of the virtual sensors with respect to the lower leg, which were a crucial part of these computations, were determined as follows: In the standard situation, the highest actuator had its virtual sensor directed to the point on the ground 100 cm in front of the participant. Likewise, the lowest actuator had its virtual sensor directed to a point on the ground 20 cm in front of the participant. Sensors associated to in-between actuators were proportionally directed to in-between points on the floor. More details concerning a similar device and concerning the relation between the digitally-computed voltages, the analog signals, and intensity of vibration can be found in Díaz et al. (2012).

3.2.4 Procedure

Initially the experimenter provided a brief explanation about the sensory substitution device and about the task: "This device includes an array of actuators that vibrate as a function of the first-encountered object on your way. If you are standing straight up, the vibration is homogeneous for all actuators. When the distance to

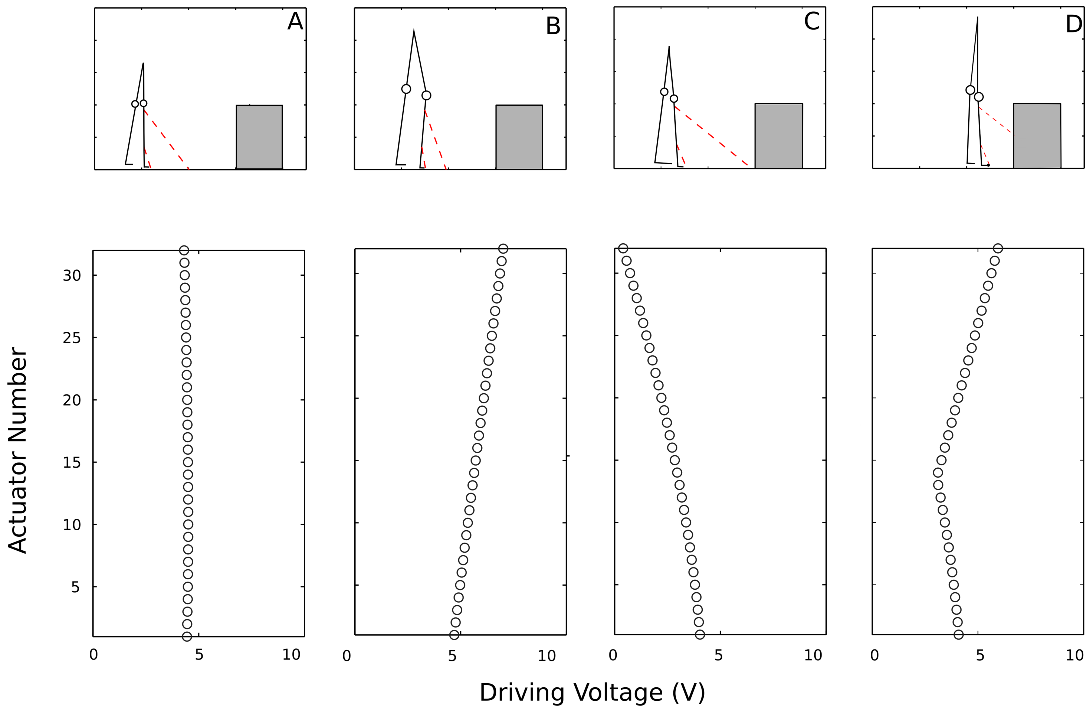

Figure 3.4: Representation of the 32 driving voltages in four common situations. The upper panels show the position and orientation of the participant's legs (continuous lines with circles representing the knees), the sensing directions of the actuators with the highest and lowest positions on the leg (dashed lines), and the cardboard box (gray area). The lower panels show the driving voltages for all actuators associated to the situations depicted in the upper panels. The vertical axis of the lower panels gives the actuator number, with 1 being the actuator with the lowest position and 32 being the one with the highest position. Four situations are represented (from left to right): A) A participant standing straight up at a sufficiently long distance from the box (the standard situation). In this situation, the driving voltage and hence the intensity of vibration is the same for all actuators. B) A posture with a forward tilt of the lower leg. The distances to the ground are shorter and the driving voltages are higher than in the standard situation. C) A posture with a backward tilt of the lower leg. In this situation the driving voltages are lower than in the standard situation. D) Participant in front of a box. Distances to the first-encountered surfaces are reduced for the virtual sensors directed to the box. As a consequence, the corresponding actuators have higher driving voltages.

the ground or to an object decreases, the intensity of the vibration of the actuators that are pointing to that surface increases. Conversely, when distance increases, the intensity of vibration of the corresponding actuators decreases. Your task is to walk through the approach area until you detect a box and to step on the box with your right foot. Only forward walking is allowed. A trial ends when you put your foot on the box. The distance to the box and its height will vary randomly." After these instructions, the experimenter attached the device and the first rigid object with markers to the participant's leg and the second rigid object to the right foot. Participants tried the device out during one preliminary trial with full vision. Participants started from the further edge of the approach area on all trials. Trials started with a "go" signal by the experimenter and finished when the participant stepped on the box, or, in case of a failure, displaced the box by kicking against it.

Participants performed three sessions of approximately one hour each on different days. During the first session participants accomplished the pretest and one practice block, during the second session two practice blocks, and during the third session one practice block and the posttest. The pretest, the four practice blocks, and the posttest each consisted of 36 trials (i.e., 36 attempts to step on the box), obtained from the factorial combination of the six above-mentioned box heights and distances. The time between the first and the third sessions was less than one week. Participants were randomly assigned to one of two groups. The vision group had full vision during the practice blocks and the no-vision group performed the practice blocks while blindfolded. All participants were blindfolded during pretest and posttest. The overall structure of the experiment is illustrated in Table 3.1.

Table 3.1: Distribution of the 36-trial test phases and the 36-trial practice blocks over the three 1-hour experimental sessions.

Session 1	**Session 2**	**Session 3**
Pretest (no vision)	Practice Block 2	Practice Block 4
Practice Block 1	Practice Block 3	Posttest (no vision)

3.2.5 Dependent Measures

The dependent variables listed in this subsection were obtained from the recorded movements. They were first automatically computed with MATLAB routines and then visually checked (and if necessary corrected) on a trial-by-trial basis. To facilitate the description of the variables, Figure 3.5 illustrates trajectories of the right foot for several representative trials.

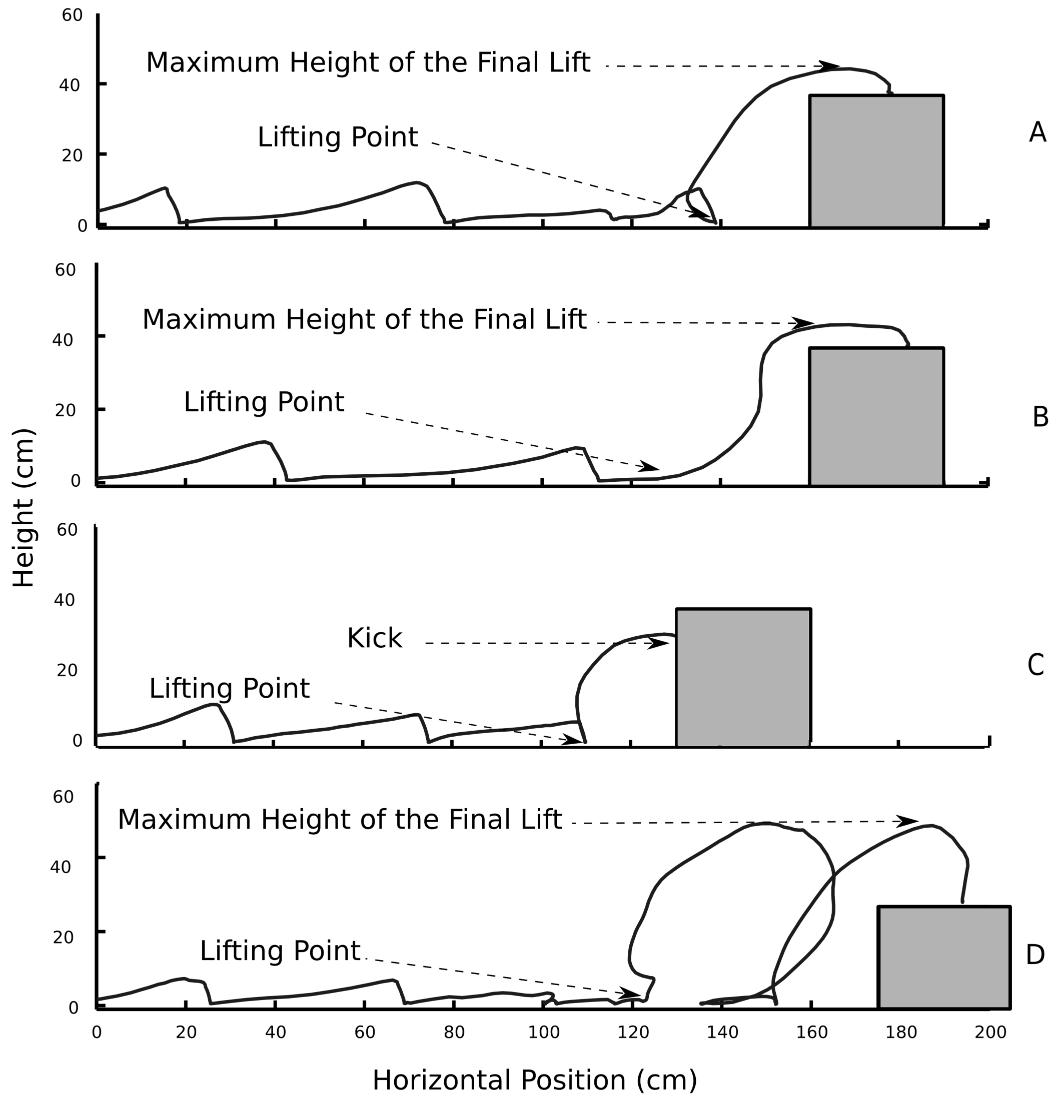

Figure 3.5: Trajectories of one participant performing four different trials. Solid black curves represent trajectories of the right foot. A) A successful trial without vision, B) a successful trial with vision, C) a trial with a kick after raising the foot, and D) a trial with a false step. As were all other trials with kicks and false steps, the trials represented in Panels C and D were performed without vision. The main points used to compute the dependent variables are identified in each of the shown trajectories.

Trial duration.

A first dependent measure, trial duration, was defined as the time between the initiation of the movement of the right foot (speed $>$ 20 cm/s) and the moment of the first contact of the foot with the box.

Kicks and false steps.

Kicks, as illustrated in Figure 3.5, were defined as cases in which participants contacted the vertical front surface of the box instead of the top of the box. False steps, illustrated in Figure 3.5D, were defined as cases in which participants lifted the foot to step on the box but in which the ground was contacted again before contacting the box, typically because the step was initiated to far from the box. Note that a strategy-dependent trade off may occur between false steps and kicks. For example, the probability of false steps is reduced at the expense of the kicks if the foot is lifted less frequently (in the extreme, not lifting the foot at all would lead to 0% false steps and 100% kicks). Because of this trade off, we analyzed the total amount of errors in addition to analyzing the kicks and false steps in isolation. The total amount of errors was defined as the sum of the kicks and false steps.

Distance between first lift and box.

For each trial with one or more lifts of the right foot, we defined the lifting point as the initiation point of the first lift. This measure is illustrated in all panels of Figure 3.5.

Height of final lift.

For trials without kicks, we determined the maximum height of the final lift, as illustrated in Panels A, B, and D of Figure 3.5.

Tilt of lower right leg.

The range of tilt of the lower right leg was defined as the maximum of the forward tilt minus the minimum of the forward tilt, in degrees and with respect to the vertical, during the interval from 2 until 1 s before the first lift. This time interval was chosen because before the lift one may expect exploratory movements and because preliminary analysis showed that in the interval from 1 until 0 s before the lift the variation in the tilt was large due to the actual lifting action.

3.2.6 Statistical Analysis

For each of the dependent variables listed in the previous section, we performed a 2×2 analysis of variance (ANOVA) with practice condition (vision, no vision) as between-subjects factor and test phase (pretest, posttest) as within-subjects factor.

3.3 Results

This section first describes the overall performance, then considers the effects of practice, and, lastly, compares the effects of the practice conditions with and without vision.

3.3.1 Overall Description of Performance

Trial duration.

On average, the trial duration was 8.24 s ($SD = 2.7$). Participants in the vision group performed the training trials with vision noticeably faster than their pretest and posttest trials without vision (6.6 vs. 7.9 s; $t(9) = 7.12$, $p < .001$). This difference reached significance also for participants in the no-vision group (7.8 vs. 8.8 s; $t(9) = 2.35$, $p = .04$), who performed the practice trials as well as the pretest and posttest trials without vision.

Kicks and false steps.

In the 36-trial pretest and posttest blocks, the mean number of errors (i.e., kicks plus false steps) was 18.8 (SD = 4.9). On average, participants had at least one error in 17.1 trials (SD = 6.9). The performance with the lowest number of errors consisted of 2 errors in a posttest (kicks in this case). The performance with the highest number of errors consisted of 35 errors in 30 trials of a pretest (30 kicks and 5 false steps). The number of kicks was larger than the number of false steps for all but one of the participants. The participant who showed a reversed pattern had 11 false steps and 6 kicks in the pretest and 10 false steps and 10 kicks in the posttest. Overall, the percentage of pretest and posttest trials without any error was 52.6%.

Distance between first lift and box.

The average distance between the lifting point and the box was 22.2 cm in the pretest and 24.0 cm in the posttest. Arguably, however, a better detection of the distance of the box with our sensory substitution device is reflected by a lower standard deviation of the distance rather than by the average distance. This is so because in contrast to a higher or lower average distance, a lower standard deviation indicates the ability to more precisely determine the point at which to lift the foot. In the following, we therefore report analyses with the standard deviation of distance as dependent variable. Let us mention that the same analyses with average distance as the dependent variable did not yield significant results ($p >$ .05).

An alternative measure for the precision of the initiation of the lift is the correlation between the position of the lift initiation and the box. On average, this correlation was 0.73. The relatively high value of this correlation indicates that the sensory substitution device provides a relatively good sensitivity to the distance of the box.

Height of final lift.

The average height of the final lift was 42.2 cm (SD = 4.7). The correlation between the height of the final lift and the box was 0.29. The moderate value of this correlation indicates that participants did not show as much sensitivity for box height as they did for box distance.

More detail is provided in Figure 3.6. The left panel of the figure shows the average pretest and posttest results for the two groups. The average height of the final step was only slightly lower for the low boxes than for the high boxes. Hence, rather than adjusting the final step to the height of the box, participants tended to make high steps. As long as the height of the step was higher than the highest box used in the experiment, this strategy allowed successful performance. For this reason, the results related to box height are less interesting and height-related results are not reported in the following sections. .

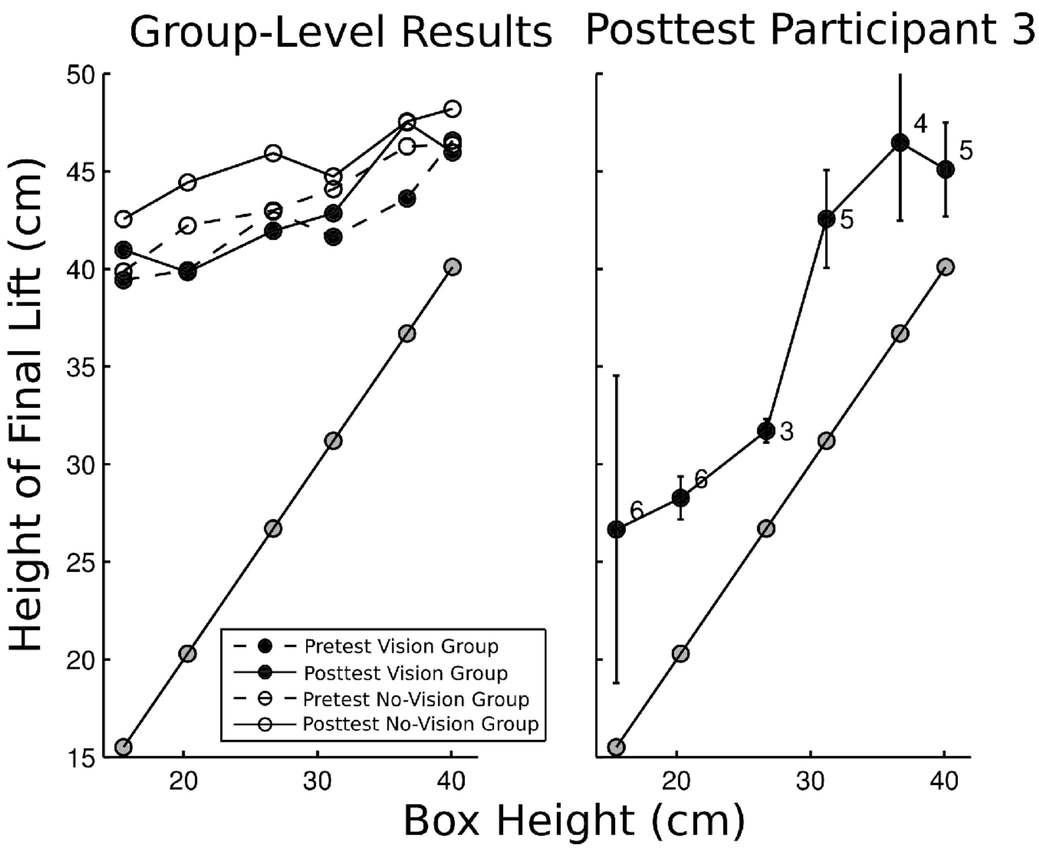

Figure 3.6: Maximum height of the final lift relative to the height of the box. Left panel: average results per group and per test phase. Right panel: posttest results of Participant 3. Error bars indicate standard deviations; numerals indicate numbers of trials used to compute the average; straight diagonal lines indicate actual box heights.

Let us mention, however, that although the average results discard that the maximum height of the steps is strongly related to the height of the used boxes, results from individual participants occasionally indicate that it may be possible to detect box height with our device. For example, for the block of trials shown in the right panel of Figure 3.6, the height of the steps appeared to be adjusted to the height of the box ($r = 0.87$, $p < .001$).

Tilt of lower right leg.

On average, 2 s before the moment of the first lift the forward tilt of the lower right leg was 7.8° ($SD = 4.7$) and 1 s before that moment the tilt was 5.9° ($SD = 6.7$). The average range of the tilt in this interval was 6.9° ($SD = 5.3$).

3.3.2 Pretest Versus Posttest and Exploration

Table 3.2 presents the results of the 2 (pretest, posttest) × 2 (vision condition, no-vision condition) ANOVAs performed on the individual block averages of the previously described measures. The main effect of practice condition was never significant (all $ps > .35$), which is not surprising because at least in the pretest one does not expect to observe group differences. We now turn to the main effect of test phase. The variables that showed a significant change from pretest to posttest ($p < .05$) were trial duration, number of kicks per trial, total number of errors (kicks plus false steps) per trial, and tilt range. Trial duration decreased from 9.10 to 7.39 s, the number of kicks per trial decreased from 0.55 to 0.35, and the number of errors per trial decreased from 0.66 to 0.43. These results indicate that performance with our sensory substitution device improved with practice.

To illustrate the significant change in tilt range, Figure 3.7 shows the average tilt angles in the pretest and posttest for the vision group (left panel) and the no-vision group (right panel) in the interval between 2 and 0 s before the moment of the first lift. During the last second before the moment of the lift, the angles increased to about 16 to 18°, indicating a forward lean at the moment of the lift. From 2 to 1 s before the moment of the lift, the average tilt angles stayed approximately constant at values of about 6 to 8° in the pretest (dashed curves), but they showed more interesting patterns in the posttest (continuous curves). In

Table 3.2: Results of 2 × 2 Repeated-Measures ANOVAs on Dependent Variables Defined in Materials and Methods Section.

Dependent Variable	**Practice Vision vs. No Vision**		**Test Phase Pretest vs. Posttest**		**Interaction**		
	$\boldsymbol{F(1,18)}$	$\boldsymbol{p}$	$\boldsymbol{F(1,18)}$	$\boldsymbol{p}$	$\boldsymbol{F(1,18)}$	$\boldsymbol{p}$	$\boldsymbol{n}$
Trial Duration	0.05	.825	20.52	<.001	0.12	.732	1388
Kicks per Trial	0.87	.368	19.34	<.001	1.62	.219	1395
False Steps per Trial	0.91	.356	1.18	.200	3.89	.064	1428
Errors per Trial	0.24	.630	26.35	<.001	4.98	.039	1394
Distance of Lift to Box (*SD*)	0.69	.410	0.92	.351	6.32	.022	1407
Tilt Range	0.36	.558	7.85	.012	0.32	.578	1237

Note. The ANOVAs were computed on the individual block averages of the listed variables (with the exception of Distance of Lift to Box, which was performed on the *SDs*; see text for explanation). The number n in the rightmost column refers to the total number of valid trials used to compute the block averages (or *SDs*).

this interval the averaged angles showed a decrease, reaching values below 3° for the no-vision group. In the Discussion (Section 3.4) we will speculate that the larger change in the tilt angles observed in the posttest may evidence a more pronounced exploratory strategy.

3.3.3 Practice With and Without Vision

Figure 3.8 shows the interaction plots for the variables listed in Table 3.2. Results for the vision and no-vision groups are given with filled dots and open dots, respectively. The majority of the plots indicate the same tendency: Practice without vision led to a steeper improvement than practice with vision. This interaction was significant ($p < .05$) for the total number of errors and for the standard deviation of the distance between the first lift and the box. The errors per trial decreased from 0.7 in the pretest to 0.4 in the posttest for the no-vision group (pretest-posttest reduction = 0.3) and from 0.6 to 0.5 for the vision group (pretest-posttest

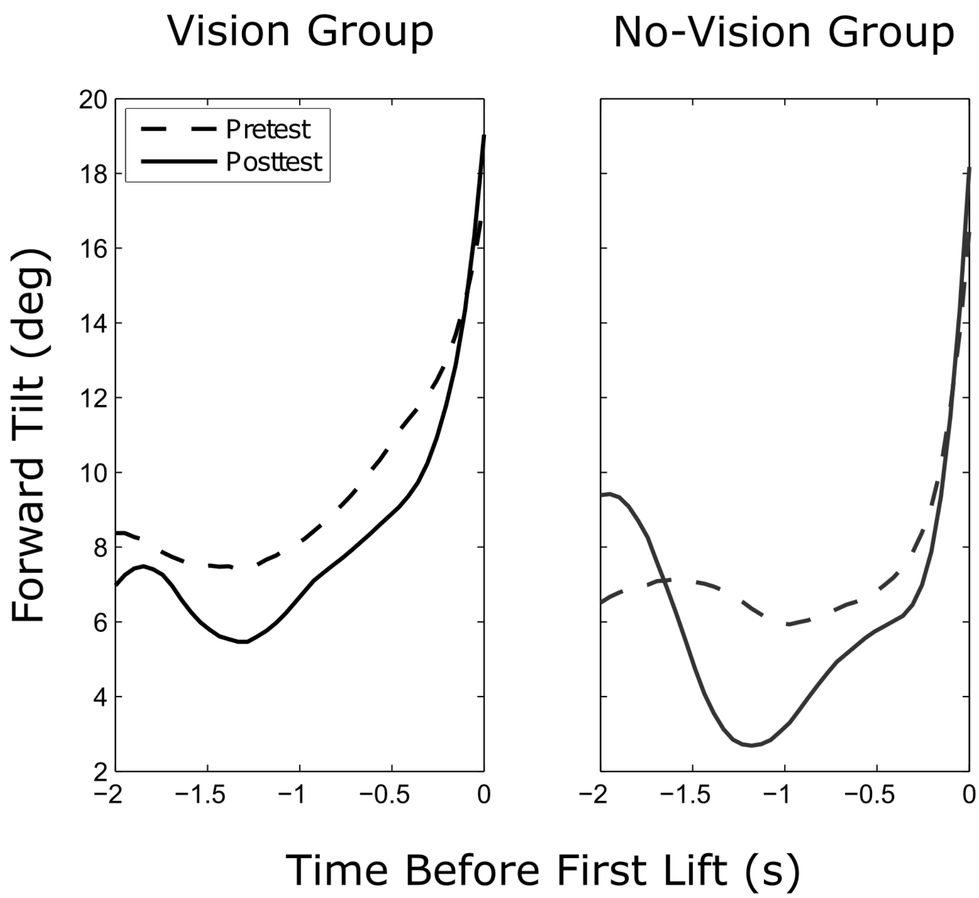

Figure 3.7: Evolution of the forward tilt of the lower right leg. Shown are the averages of the tilt angles in the final 2-vision groups. In the posttest, a decrease in the tilt can be observed between -2 and -1 s, leading to a larger tilt range in that interval.

reduction = 0.1). The standard deviation of the lift-box distance decreased from 22.3 cm in the pretest to 14.6 cm in the posttest for the no-vision group (pretest-posttest reduction = 7.7 cm) but increased from 14.2 to 17.7 cm for the vision group (pretest-posttest reduction = -3.5 cm). To summarize these results, practice without vision leads to fewer errors and to a more precise control of the moment of the first lift.

3.4 Discussion

The aim of this research was threefold. First, we wanted to determine if it is possible to detect and step on ground-level obstacles with our sensory substitu-

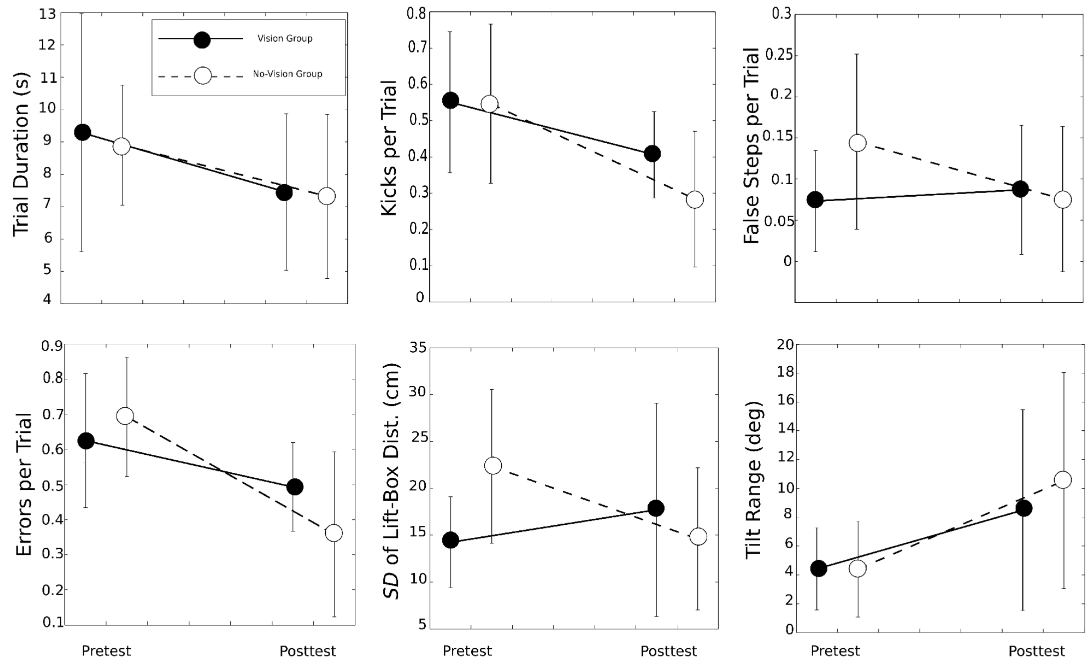

Figure 3.8: Interaction plots for the main dependent variables. Each graph shows the average value of one variable per test phase and per group. The variable names are indicated on the vertical axes. The significance levels indicated by asterisks correspond to the ones given in Table 3.2. Error bars represent standard deviations.

tion device on the lower leg. Second, we wanted to know if performance improves with practice. Third, we tested if different practice conditions have different effects on performance. Our results indicate that these questions can be answered affirmatively.

With regard to our first aim, the average percentage of trials that were performed without errors was relatively high given the difficulty of the task (the task was difficult because the location and height of the box were varied from trial to trial). Furthermore, substantial variability was observed among participants: Whereas some participants were very successful, others were less so. In addition to the relatively high average performance, the performance of the more successful participants proves that the sensory substitution system offers enough information to complete the task. This may be interpreted as support for the construction of sensory substitution systems that are lightweight, allow a high level of mobility, and have an on-line coupling of the detected information to the novel stimulation so that users can exploit the new sensorimotor couplings (O'Regan & Noë, 2001; Lenay et al., 2003; Auvray & Myin, 2009).

One of the factors that may have contributed to the relatively high levels of performance is the fact that the stimulation provided by our device was computed as a function of distance. A substantial number of other devices use light intensity detected by a camera as the basis of the stimulation. Light detected by a camera shows large fluctuations due to changes in illumination and shading effects caused by moving objects. Our visual system has evolved to detect invariant patterns that specify (action-related) properties of interest from these fluctuations (Gibson, 1979). It is unrealistic, however, to expect that perception with sensory substitution devices can reach the sophistication of the visual system. Distances are not affected by fluctuations due to illumination and shading. We therefore believe that distance-based sensory substitution may eventually lead to more successful sensory substitution devices (cf., Cancar et al., 2013; Cardin et al., 2007; Díaz, Barrientos, Jacobs, & Travieso, 2011; Díaz et al., 2012; Warren & Strelow, 1984). Note in this regard that experiments with light-intensity-based devices are often performed in well-controlled environments with predominantly black and white objects (e.g., Guarniero, 1974).

It is interesting to observe that users of our device were able to perform the task despite the poor tactile acuity of the lower leg. In this sense, the strategy that we followed in the development of the device is innovative. Most authors assume that the sensitivity of the skin is among the important criteria to choose the part of the body to place a sensory substitution device (Jones & Sarter, 2008; van Erp, 2007). Our device, in contrast, is placed on the body segment most relevant to the task at hand. Thus, rather than the sensitivity of the considered body part, what may be important is the suitability, to the task at hand, of the stimulation and of the sensorimotor contingencies provided by the device. Our results show that the design of our device is suited to the control of the final step with regard to the distance of the obstacle.

The evidence for the suitability of the device to control the step as a function of the height of the box is weaker. This may be so because our experimental task allowed a strategy that did not require the detection of information about box height: Participants frequently performed steps that were high enough even for the highest box. The fact that participants seemed to use a strategy that kept a part of the performed action constant, possibly because of the difficulty to detect the informational basis of that part of the movement, is reminiscent to a previously reported study about weight perception through dynamic touch (Fleury et al., 1995). In that study, a deafferented patient showed more reproducible wielding patterns than control subjects with intact proprioception. The constancy shown by the deafferented patient allowed her to estimate the weight of the lifted object visually. Hence, both the deafferented patient in Fleury et al. (1995) and the participants in our study discovered a way to perform an action successfully while performing a part of the action in way that does not require the typical informational basis of that part of the action—information about box height in our case and proprioceptive information in the case of Fleury et al.

With regard to our second aim, we observed that after practice the task was performed faster and with fewer errors (specifically with fewer kicks). This is consistent with a substantial number of previous studies that report effects of practice with sensory substitution devices (e.g., Auvray et al., 2007; Epstein et al., 1989; Kim & Zatorre, 2008; Nagel et al., 2005; Proulx et al., 2008; Segond et al., 2005; Warren & Strelow, 1984). We also observed a significant effect of practice on the variable tilt range, which indicates the amount of forward-backward tilt of the lower leg with the device (during a certain time interval before the leg is lifted to step on the box). In the pretest, participants showed relatively little variation in the tilt; in the posttest, the range of variation was larger. This pattern may highlight the role of exploration. Changes in the tilt of the leg cause changes in the orientation of the virtual sensors of the device, and, as a consequence, in the pattern of vibration on the leg. Such changing patterns may help the user to detect the environmental properties that co-determine the vibratory patterns (e.g., the presence of an obstacle). Previous studies in the field of sensory substitution that addressed the role of exploratory movements include Díaz et al. (2012) and Rovira, Gapenne, and Ammar (2010).

A hypothetical change in exploratory movements with practice can be related to previous studies in the field of dynamic touch. Perceptual and perceptual-motor learning is often associated with a change in which informational variables are detected (Jacobs, Silva, & Calvo, 2009; Michaels et al., 2008). The detection of particular informational variables, in turn, is associated with particular exploratory movements made to detect these variables (Michaels & Isenhower, 2011), leading to the claim that performance improves because learners come to make better exploratory movements (Arzamarski, Isenhower, Kay, Turvey, & Michaels, 2010). This reasoning indicates that changes in exploratory movements made with sensory substitution devices are consistent with the view that users improve because they come to detect more useful informational variables with the devices.

One may note from the lower right panel of Figure 3.4 that, with the current configuration of the system, the nearness of an obstacle goes together with an increased vibration of the higher actuators and with a discontinuity (in the figure at Actuator 14) of the change in vibration over the array of actuators. Our results demonstrate that such patterns, their change over time, and/or their sensorimotor coupling to exploratory actions contain information that allows the stepping action. We do not have more precise knowledge about the informational variables that are used by novices and by experts and about how these variables are detected. Achieving such knowledge would be interesting for theoretical reasons and because it may form the basis of more advanced training methods, for instance if this or a similar system is to be used as an assistive device. This is so because, if knowledge about variable use is available, then training methods can be based on the manipulation of the usefulness of the variables typically used by novices so that these graduate more quickly toward the variables typically used by experts (see Huet et al., 2011; Jacobs, Runeson, & Michaels, 2001; Smeeton, Huys, & Jacobs, 2013, for applications of this methodology in other sensory domains).

With regard to our third aim, practice without vision led to a larger reduction in the number of errors and a larger increase in the precision of the initiation of the final lift than practice with vision. These findings may be related to the guidance hypothesis (Salmoni, Schmidt, & Walter, 1984; Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009). This hypothesis holds that the more learners rely on some type feedback during practice, the more they come to depend on that feedback. Such a dependency has a detrimental effect on performance when the feedback is withdrawn. During practice with vision, our participants may have depended to a large extent on vision. As a consequence, these participants may not have learned to guide their action on the basis of the vibrotactile information as succesfully as participants that practiced without vision. In short, although vision was not found to prevent learning entirely, our results show an advantage of practice without vision and are hence consistent with the guidance hypothesis.

Let us conclude with two aspects that we consider crucial to the field of sensory substitution. First, we agree with Durette and colleagues (2008) that laboratory experiments run the risk of being more of interest to scientists and designers than to users. This is so in part because laboratory studies do not always address practically relevant tasks. With the task chosen in the present study, we have aimed to make a step in a posive direction in this regard. Second, we agree with Lenay and colleagues (2003) that there is a need to focus on training programs for coming to be proficient in the use of sensory substitution devices. In this sense our study shows that training without vision has advantages over training with vision.

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Chapter 4

Body-Scaled Affordances in Sensory Substitution

The research[1] field on sensory substitution devices has strong implications for theoretical work on perceptual consciousness. One of these implications concerns the extent to which the devices allow distal attribution. The present study applies a classic empirical approach on the perception of affordances to the field of sensory substitution. The reported experiment considers the perception of the stair-climbing affordance. Participants judged the climbability of steps apprehended through a vibrotactile sensory substitution device. If measured with standard metric units, climbability judgments of tall and short participants differed, but if measured in units of leg length, judgments did not differ. These results are similar to paradigmatic results in regular visual perception. We conclude that our sensory substitution device allows the perception of affordances. More generally, we argue that the theory of affordances may enrich theoretical debates concerning sensory substitution to a larger extent than has hitherto been the case.

[1]This chapter is published with the next reference: Travieso, D., Gómez-Jordana, L., Díaz, A., Lobo, L., & Jacobs, D. M. (2015). Body-Scaled affordances in sensory substitution. *Consciousness and Cognition, 38*, 130–138. doi:10.1016/j.concog.2015.10.009

4.1 Introduction

4.1.1 Body-Scaled Affordances in Sensory Substitution

A sensory substitution device (SSD) allows the substitution, or enhancement, of the capabilities of a particular perceptual system through an alternative one. Since pioneering devices such as the Optacon (Linvill & Bliss, 1966) and the TVSS (Bach-y-Rita et al., 1969), technological advances have progressively improved the portability and usability of SSDs (Dakopoulos & Bourbakis, 2010; Jones & Sarter, 2008; Visell, 2009). Even so, a wide generalization of the use of SSDs has not occurred (Spence, 2014).

The majority of SSDs substitute vision through either the tactile or the auditory modality. In these devices, the light intensity detected by a camera is transduced to stimulation patterns ranging from electrotactile or vibrotactile intensity to pitch range. An outstanding example of an auditory SSD is the vOICe (Auvray et al., 2007; Proulx et al., 2008; Striem-Amit et al., 2012). The vOICe transforms information about the orientation and position of visual edges detected by a camera into sounds with different onsets and pitches.

Beyond the scientific and technical challenge of developing and implementing SSDs, the possibility of substituting a perceptual system raises questions concerning theories of perception and perceptual consciousness. One of the classic questions that have been raised in this regard refers to the conceptual boundary between true sensory substitution and cognitive aids. In true sensory substitution users report perceiving objects out there, in the environment, rather than attending to the stimulation on the sensory surface. The term distal attribution is devoted to this conscious experience of external objects. On the contrary, a cognitive aid is a device that translates information about the external world into arbitrary signs. In this case, users perceive the signs and infer the objects through association. Whereas cognitive aids require explicit learning of signs, codes, and the corresponding meanings, true substitution is intended to make distal attribution emerge through a lawful coupling of perception, action, and sensorimotor information, without the explicit learning of codes.

Several authors have claimed that their SSDs elicit distal attribution. Such claims can be found, for example, in the contributions of Guarniero (1974, 1977) with the original TVSS, in several studies with the vOICe (Auvray et al., 2005; Proulx, 2010; Ward & Meijer, 2010), and in studies with other visuo-tactile SSDs (Segond et al., 2005; Siegle & Warren, 2010). Other authors have explicitly considered their SSDs to be cognitive aids, as is the case, for example, for the NavBelt (Johnson & Higgins, 2006) and the NAVIG (Kammoun et al., 2012). However, in a large number of cases no clear-cut distinction is made between these two categories. In addition, no generally agreed-upon sensorimotor behavior or technical feature of the SSD has been proposed that allows one to unambiguously differentiate true sensory substitution from cognitive aids.

Distal attribution may be argued to be the result of the mastery of certain sensorimotor contingencies (Auvray et al., 2005; O'Regan & Noë, 2001). However, given that the majority of SSDs allow an active control of the sensor component and the effector component is lawfully coupled to the sensor component, according to such criteria the majority of SSDs may produce distal attribution. A related criterion to classify a device as to belonging to the true substitution category or the cognitive aid category is the analysis of *how* the sensory information is transformed in stimulation. In true substitution, one may argue, the contingency of the perceiver's movements and the stimulation should be derived from certain physical laws, such as the laws of optics or acoustics, whereas this is not the case for the relation between external objects and the (arbitrary) codes of cognitive aids. Emphasizing the importance of physical laws for perception and action is reminiscent to an approach that, we believe, is of broader relevance to the main theoretical debates in sensory substitution: ecological psychology.

4.1.2 The Control of Action and Body-Scaled Metrics

One of the theoretical and empirical fields that have received wide attention from ecological researchers is that of affordances. The concept of *affordance* was coined by Gibson (1979). Affordances for a particular perceiver are the possibilities for action for that perceiver. This means that affordances are environmental properties that are relevant to the perceiver. Proponents of the ecological approach hold that affordances constitute the object of perception.

According to Fajen, Riley, and Turvey (2008), five main features characterize affordances. First, affordances are real. That is, ontologically, affordances are actual properties of the organism-environment system. Second, affordances are animal-specific. This means that they are not intrinsic properties of objects, but relational properties defined with respect to a perceiver. Third, affordances capture the reciprocity of perception and action, meaning that the perception of the environment is in terms of the possible actions that the perceiver can produce and, at the same time, affordances are perceived through active exploration of the environment. Fourth, affordances allow the prospective control of action. That is, by making use of affordances, a perceiver can adjust her behavior to a future state of the environment, lawfully predicted from the current state. Fifth, affordances are meaningful, so that instead of perceiving the environment in neutral terms as extent, mass, and so forth, affordances are perceiver-relevant properties as climbability, catchability, etc.

Fajen et al. (2008) distinguished *body-scaled* and *action-scaled* affordances. The latter concept refers to possibilities for action that are made possible by dynamic action-capabilities of the perceiver. Tasks that have been used to study this type of affordance include the control of braking (Lee, 1976), catching fly balls (Fajen, Diaz, & Cramer, 2011; Oudejans, Michaels, Bakker, & Dolné, 1996), and walking through sliding doors (Fajen & Matthis, 2011; Fajen et al., 2011). Body-Scaled affordances refer to properties that are scaled to anthropometric dimensions. Research concerning this type of affordance has addressed stair climbing (Konczak, Meeuwsen, & Cress, 1992; Mark, 1987; Warren, 1984; Wraga, 1999), prehension (Newell, Scully, Tenenbaum, & Hardiman, 1989; Newell, McDonald, & Baillargeon, 1993; van der Kamp, Savelsbergh, & Davis, 1998), sitting (Mark, 1987), passing under a barrier (van der Meer, 1997), fitting the hand through an aperture (Ishak, Adolph, & Lin, 2008), and walking through apertures tightly scaled to the inter-shoulder dimension (Warren & Whang, 1987).

How may the key ecological concepts relate to the theoretical debates in sensory substitution and, more particularly, to the debate concerning distal attribution? First, distal attribution is most commonly suggested to concern properties of the world that are independent of the observer, such as the distance or the dimensions of an object as measured in metric units. Because these properties are distal properties (i.e., exclusively belonging to the external world), the distal part of the term distal attribution makes sense. Given that this view is the dominant one in the debate on distal attribution, it is not typically questioned that awareness should eventually be of distal properties.

The ecological shift away from the claim that perceivers are aware of perceiver-independent properties and toward the claim that perceivers are aware of relational properties may reorient the debate concerning distal attribution in the field of sensory substitution. As mentioned, in the ecological view one perceives properties that are best described in terms such as “an aperture that I can pass through”, “a step that I can climb”, etc. Because these properties are not exclusive of the external world, the *distal* part of the term *distal attribution* looses part of its meaning. Although a deeper analysis of the concept of affordance is beyond the scope of our article, it is important to note that affordances are instantiated in ecological properties that are scaled to the perceiver. It is also interesting to note that similar claims concerning relational properties have been made in other scientific areas (e.g., in quantum physics; Gomatam, 1999).

A second key claim of the ecological approach is that affordances are perceived in a direct manner, meaning that perception is not mediated by mental representations, inferential processes, or other computational processes (Michaels & Carello, 1981; Gibson, 1979). Although relevant to the debate, this claim cannot be verified empirically. Nevertheless, we believe that it would be illustrative to analyze perception with SSDs using the tools that are typically used in the ecological literature. Such an analysis may confirm that canonical results of the ecological approach in regular perception are also obtained with SSDs. Showing that empirical results with SSDs mirror key empirical results for regular perception may be interpreted as tentative support for the claim that the main theoretical claims of the ecological approach for regular perception are valid also for perception with SSDs. To exemplify this reasoning, the present study aims to replicate Warren’s (1984) classic results concerning the stairclimbing affordance with an SSD.

4.1.3 π-numbers in Stair Climbing

Warren (1984) asked participants to estimate if they felt able to climb a step in a bipedal manner. His experiments used different step heights and two groups of participants: one *tall* and one *short*. As expected, the steps that were judged climbable were higher for the tall group than for the short group. Warren proposed a simple biomechanical model to describe the expected maximum step height as a function of the length of the leg. This model, illustrated in Figure 4.1, is given by the equation

$$R_c = Leg + ULeg - LLeg \tag{4.1}$$

In this equation, R_c refers to the critical step height, *Leg* refers to full leg length, *ULeg* refers to upper leg length, and *LLeg* refers to lower leg length. Equation 4.1 allows one to derive the value of R_c from anthropometric values. One may assume that the value of R_c corresponds to the step height that leads 50% of affirmative climbability judgments. Warren (1984) showed that the climbability affordance can be described with a dimensionless number called critical π-number. The critical π-number (π_c) refers to the maximum height that a participant is able to climb in a bipedal manner scaled to her leg length. This number can be defined as

$$\pi_c = R_c/L \tag{4.2}$$

Warren observed that the group differences in the climbability judgments disappeared after scaling the height of the steps to the leg length of participants: Both experimental groups showed the expected value of $\pi_c \approx 0.88$. In the present study, we test if participants using an SSD are able to perceive affordances. More specifically, we test if participants estimate the climbability of steps in the same way as the participants in Warren's (1984) regular visual perception study. We hypothesize that perception with an SSD shares the body-scaled nature observed for visual perception.

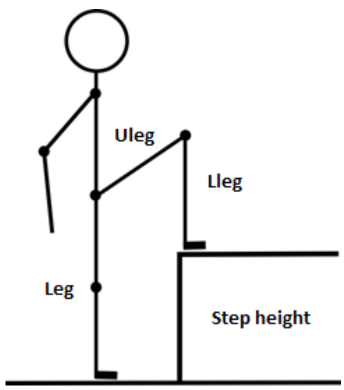

Figure 4.1: Biomechanical model of stair climbing. Adapted from Warren (1984).

4.2 Materials and Methods

4.2.1 Participants

Two groups of eight male participants performed the experiment. Individuals in the *tall* group had a mean height of 182.5 cm (SD = 1.3 cm) and were taller than the 75th percentile for height reported in the tables of the Centers for Disease Control and Prevention (CDC, 2002). Individuals in the *short* group had a mean height of 169.1 cm (SD = 2.2 cm) and were shorter than the 25^{th} percentile for height (CDC, 2002). All participants signed an informed consent form prior to the experiment. The research program was approved by the local committee of ethical research (CEI 52-957).

4.2.2 Design

Following Warren's (1984) design, two independent variables were considered. The first independent variable was the height of participants (i.e., the *tall* and *short* groups). The second independent variable was the height of the to-be-judged steps. Seven step heights were used, ranging from 45 to 105 cm. Our steps were similar to ones used by Warren, who used seven steps heights ranging from 50.8 to 101.6 cm. In our experiment, each step height was used five times, resulting in 7 (step heights) $\times$ 5 (repetitions) = 35 trials per participant. The order of the trials was randomized per participant.

4.2.3 Apparatus and Setup

Figure 4.2 illustrates the experimental setup. The setup included an exploration area of approximately 400×80 cm, a raised platform (i.e., the step) located 50 cm beyond the end of the exploration area, and a four-camera motion-capture system (Qualisys Inc., Sweden). Participants wore a vibrotactile SSD that was initially designed for previously reported experiments (Díaz et al., 2012). The SSD consisted of a vertical array of 24 coin motors whose vibration was a function of the distance to the first-encountered object in a frontal body referenced direction. The vertical array of actuators was located between the top part of the chest and the navel, about 4 cm to the left of the sternum (from the perspective of participants). A rigid body (a piece of cardboard with reflective markers) was also attached to the chest (near the actuators). The motion tracking system continuously registered the position and orientation of the rigid body formed by the reflective markers and exported these measures to Matlab.

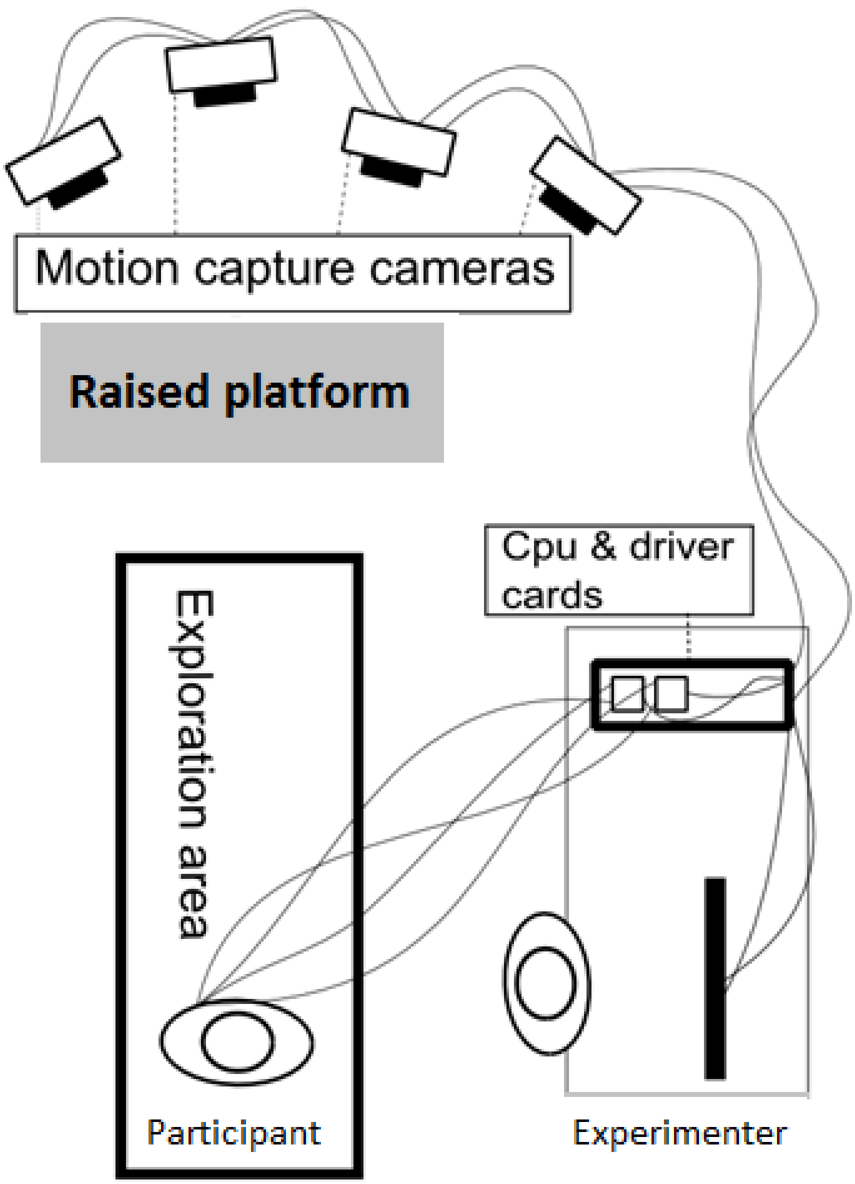

Figure 4.2: Experimental setup.

Self-developed Matlab routines used the imported position and orientation of the rigid body to compute the position and orientation of the participant, and hence of each actuator. The position and orientation of each actuator, in turn, were used to compute the distance from the actuator to the first-encountered object in the pre-established frontal direction (see Figure 4.3). In this experiment, the first-encountered object was either the floor or the step. As mentioned, the driving voltage of each actuator was computed as a function of the distance to the first-encountered object; the nearer the object, the higher the driving voltage. Finally, the driving voltages were sent to the coin motors. The system cycled through the computations with a frequency of about 20 Hz. Figure 4.3 illustrates the functioning of the SSD in three situations.

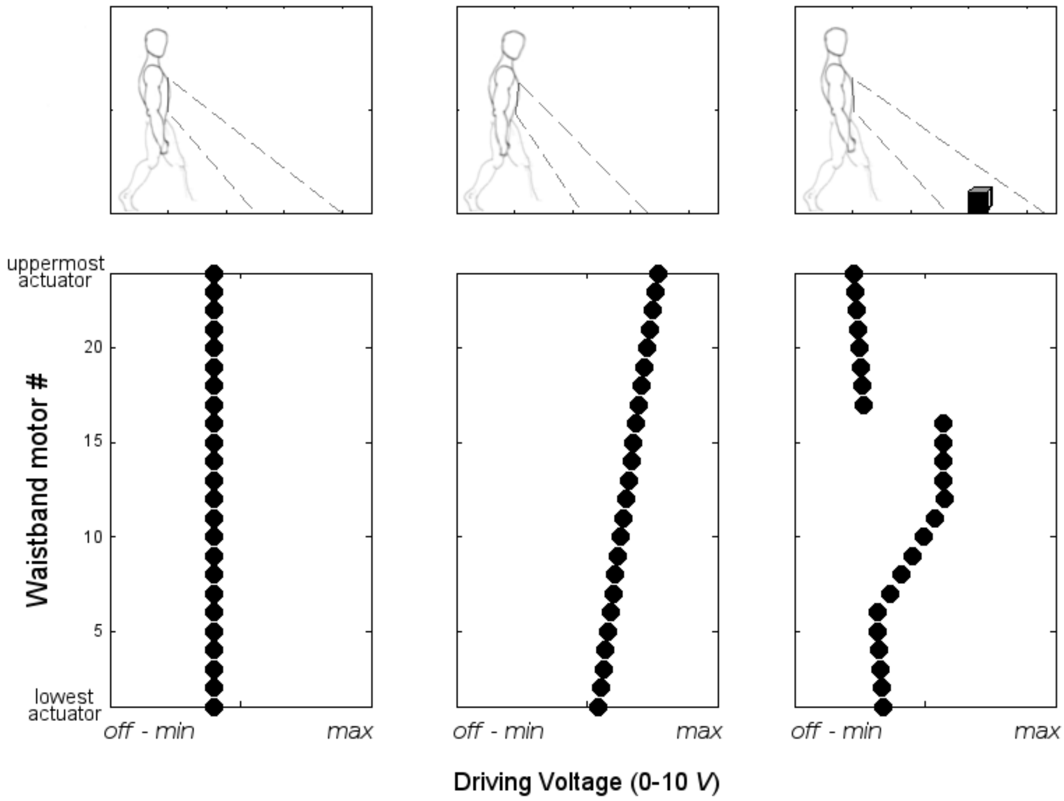

Figure 4.3: Schematic representation of the functioning of the SSD. Upper panels show participant positions and the ground range that is "in sight". Lower panels show the corresponding activation of the vibrating motors.

The panels on the left illustrate a user standing straight up in a situation without a step. In this situation, the sensory direction of the highest actuator was oriented to a point on the ground 3.0 m ahead, the lowest actuator was oriented to a point on the ground 1.5 m ahead, and the in between actuators were oriented to in-between points on the ground. The lower left panel illustrates that, in this situation, a constant low voltage level was used for all actuators. When the participant moved, the orientation and position of the actuators and the associated body-referenced sensory directions changed, resulting in changes in the distances to the floor (or to the step) along the sensory direction of the actuators. The middle panels of Figure 4.3 show a situation in which the participant leaned slightly forward, resulting in shorter distances and hence higher driving voltages, especially for the higher actuators. The right panels show a situation with a step. In this situation the distances to the first-encountered object and the associated driving voltages changed in a less homogeneous manner over the actuators than in the situations shown in the left and middle panels. A more detailed description of the used SSD is provided in Díaz et al. (2012). An alternative (portable) version using a Microsoft Kinect sensor (without the need of external position tracking and virtualization) is described in Cancar et al.(2013; cf. Lobo, Travieso, Barrientos, & Jacobs, 2014).

4.2.4 Procedure

Participants were first measured anthropometrically, allowing us to calculate the biomechanical model. Then, they received the following instructions: "The vibration of the actuators is a function of the distance to the ground. The vibration is uniform if you are standing straight up and there is a flat surface in front of you. If you lean forward, the vibration becomes more intense because the actuators get closer to the ground; if you lean backward, the vibration becomes less intense because you are not focusing on the ground. Similarly, if an obstacle is present, the area of the array that points toward the object vibrates more intensely because the distance between the actuators and the nearest object is reduced. Now I am going to present you steps of different heights. At the end of each trial, you will be asked to tell me if you think you are able to climb them without using your hands. You should not leave the exploration area during the trial. Once blindfolded I will tell you if you are about to leave the exploration area, so you can avoid leaving it." To clarify the explanation we used the images presented in Figure 4.3.

Before the actual experimental trials, nine practice trials were performed with three repetitions of the smallest (45 cm), medium (75 cm), and highest (105 cm) steps. In these trials, a wooden platform that was adjustable in height was used, and participants perceived both through the SSD and through regular vision (i.e., they were not blindfolded). Participants were not allowed to touch the steps at any moment. These practice trials were immediately followed by the 35 experimental trials. Each trial lasted 30 s. Participants started at the furthest end of the exploration area, and they were allowed to walk back and forth in the area. The experimenter warned participants verbally when they closely approached one of the edges of the exploration area, in order to avoid that they left the area. When the 30-s trial ended (i.e., when the vibration stopped), participants made a forced-choice judgment concerning the perceived bipedal climbability. No feedback was given. In the experimental trials participants were blindfolded and virtual steps were used. The virtual steps affected the vibration as described above without being physically present. The physical presence of the steps was not necessary because, during the experimental trials, participants were blindfolded and did not have physical contact with the steps.

4.3 Results

We performed a two-way ANOVA on the proportion of trials in which participants judged the step to be climbable in a bipedal way. The within-subjects factor was the height of the step (seven levels) and the between-subjects factor was group (tall vs. short). Significant main effects were observed for step height, $F(6, 84) = 27.64$, $p < .001$, and group, $F(1, 14) = 5.41$, $p = .04$. The interaction was not significant: $F(1, 32) = 0.95$, $p = .34$. As can be seen in Figure 4.4, as the steps increased in height, the proportion of steps that were perceived as climbable progressively decreased. The figure also shows that this proportion was higher for the tall group than for the short group.

To illustrate the stair climbing affordance as done by Warren (1984), it is necessary to establish the height with 50% affirmative judgments (which is assumed to correspond with the critical step height, R_c, as defined in Equation 4.1). To do so, we fitted logistic functions to the probability data, using the equation

$$p_(climbable) = \frac{1}{1 + e^{-a+bx}} \tag{4.3}$$

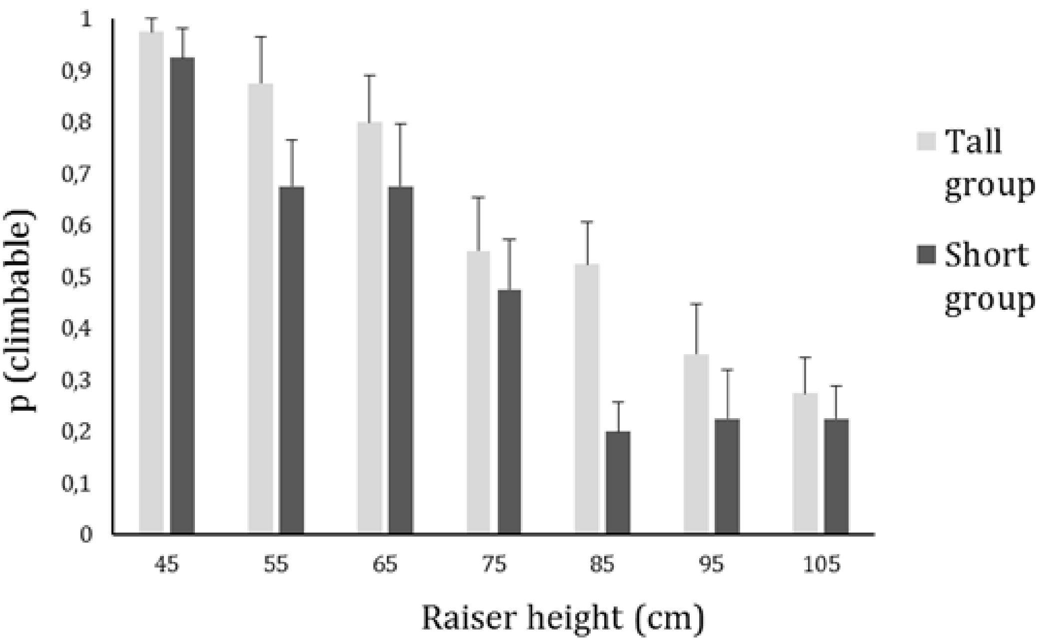

Figure 4.4: Proportion of affirmative judgments as a function of step height and group.

Figure 4.5 shows the fitted curves for the tall and short groups. We performed a t-test on the critical step heights (R_c) that were obtained from the logistic curves of individual participants. The effect of group was significant: $t(14) = 2.12$, $p = .003$. The tall group indeed judged that they could climb higher steps ($M = 84.39$ cm, $SEM = 3.57$) than the short group ($M = 74.85$ cm, $SEM = 2.76$).

We next rescaled the results as the ratio of step height by leg length. We performed the same logistic fits on the rescaled data as on the original data. Figure 4.6 shows the resulting curves. A t-test on the individual critical π-numbers (π_c) did not show a significant group difference: $t(14) = 0.75$, $p = .46$. Finally, we performed a t-test to check if our overall π_c was different from .88 (the value reported by Warren, 1984). The overall π_c in our sample was not significantly different from .88: $t(15) = 0.99$, $p = .34$. In our case π_c was 0.91.

In addition to the similarity of the observed values of π_c, it is interesting to note that our response curves and the ones reported by Warren (1984) differed in the sense that our curves were less steep. For example, whereas Warren reported 0%

and 100% of climbable responses for step heights of 101.6 and 50.8 cm, respectively, we did not observe percentages as low as 0% nor did we observe percentages as high as 100%. This difference can be interpreted as reflecting the lower acuity of perception with an SSD as compared to regular visual perception. Note, finally, that whereas our data show a relatively continuous decline of the percentage of climbable responses with riser high for the *tall* group, the decline seemed to be slightly less continuous for the *short* group. We do not have an explanation for this latter finding.

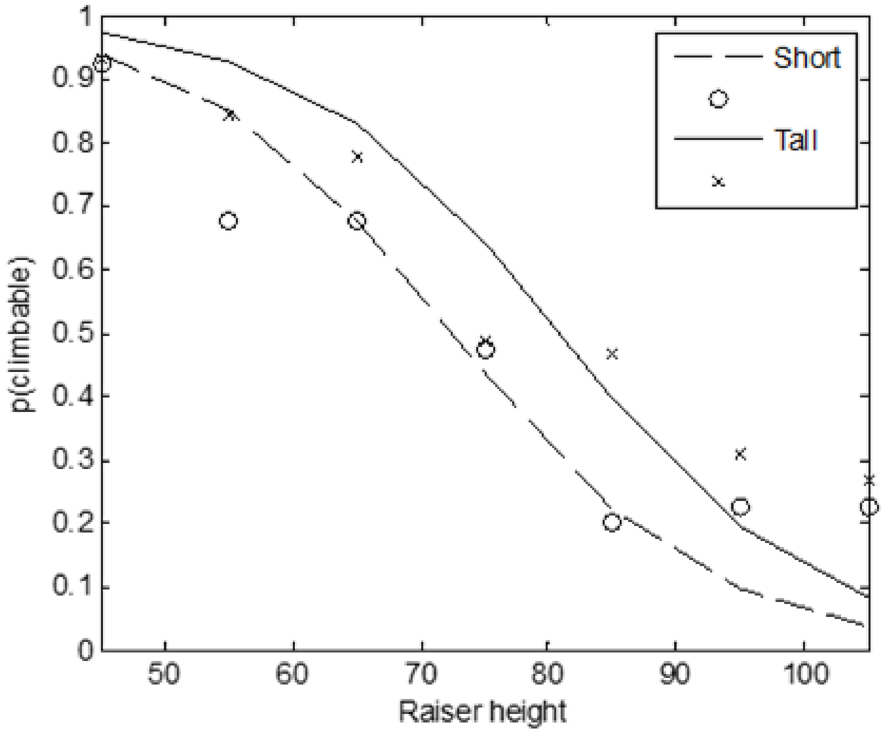

Figure 4.5: Logistic fits of p(climbable) as a function of step height for both experimental groups.

4.4 Discussion

The rationale of the present study was to test if SSDs allow the perception of affordances. As a case study, we addressed the perception of climbability through a vibrotactile SSD. It was shown that tall users of our device have a higher mean threshold of climbable steps than short users. However, when the height of the steps is scaled to the length of the leg of the users, then tall and short users do not differ in the height that they perceive as climbable. In sum, perception with our SSD is not of a primary quality of the object, height, but of a relevant relational property, climbability. A similar distinction between primary and secondary qualities, in a different scientific area, has addressed by Gomatam (1999).

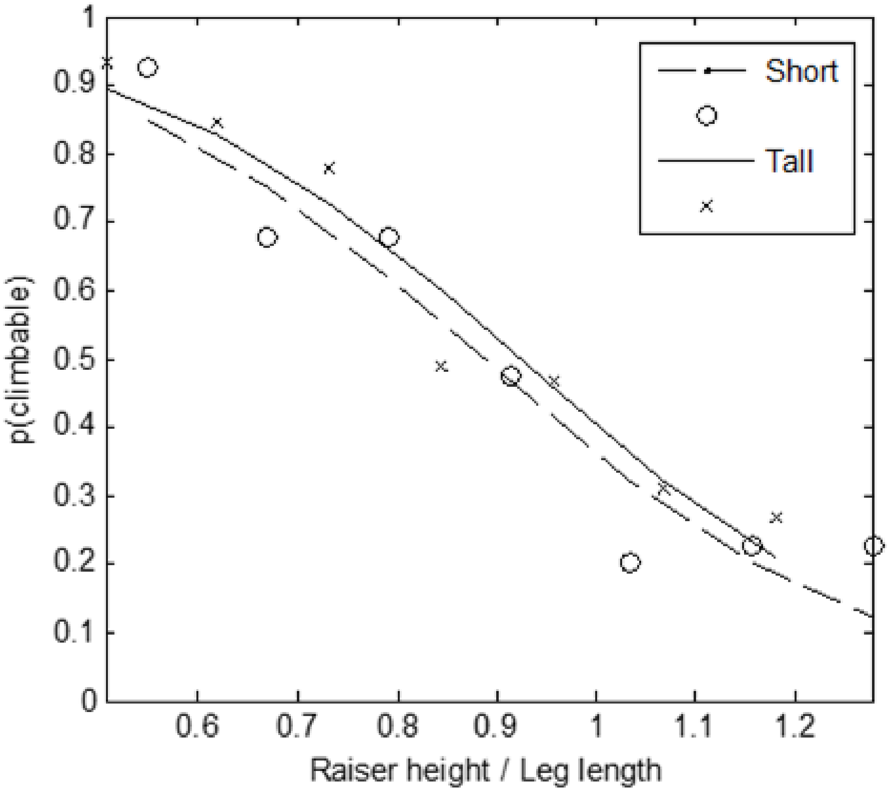

Figure 4.6: Logistic fits of p(climbable) as a function of step height divided by leg length for both experimental groups.

With respect to the critical π-number of this affordance, our results for perception with an SSD did not differ significantly from those reported by Warren and Strelow (1984) for visual perception, establishing the π-number for critical step height around $\pi_c \approx .88$. Given that the proprioceptive components of the tasks are not different, the perception of the steps does not appear to differ between regular vision and SSD perception, at least on the crucial aspect considered in our analysis. Our conclusion, therefore, is that our vibrotactile SSD allows the perception of body-scaled affordances, albeit with less acuity than regular visual perception. The observed similarity between different ways of perceiving is reminiscent to Gibson's concept of perceptual systems and, in particular, with his idea that "the pattern of the excited receptors is of no account" (Gibson, 1966, p. 4).

Relatedly, in the introduction of this article we have argued that adopting key ecological tenets, such as the claim that perception is of affordances, may be of relevance to theoretical debates in the field of sensory substitution. Let us also speculate that an objective measure of π-numbers of either action-scaled or body-scaled affordances may be a useful part of tests that aim to classify SSDs as producing true sensory substitution (i.e. distal attribution) or as being a cognitive aid. Our main argument is that the perception of affordances emerges from active exploration, the resulting sensorimotor contingences, and the biological demand to perceive relevant relational properties. In so doing, a stable objective measurement can be obtained in the form of dimensionless informational numbers that can be tested experimentally. A cognitive aid that, say, indicates the presence of a particular object or letter with a particular vibratory code, might be expected to be less likely to produce the perception of body-scaled affordances.

In addition to concluding that body-scaled affordances are perceived with our SSD, one may consider the question of how such affordances are perceived. The main ecological tenet in this regard is that affordance are perceived directly. We are aware, however, that assuming that the observed π-number provides evidence for direct perception might not result convincing to many, as the skeptic argument may always be held. Even in regular vision, the skeptic concerning direct perception may always considered perception a compositional process that starts with minimal units of information that are later integrated and added to secondary properties in an automatic and unconscious manner, perhaps in a computer-like fashion via symbol manipulation. Likewise, possible claims about direct perception with SSDs are always open to criticism, which may mirror the skeptic argument in the case of regular vision (Fodor & Pylyshyn, 1981; cf. Turvey, Shaw, Reed, & Mace, 1981). If, on the other hand, one chooses to place the burden of proof on the skeptic, one may also argue that replicating a sufficient number of key ecological results, such as the observed π-numbers, sets perception with SSDs in reference to direct perception at the same status as regular visual perception.

Although the main topic of the present article is the perception of affordances, we now briefly address another main concern of ecologically inspired research: the informational basis of actions. According to Cesari, Formenti, and Olivato (2003), the perceptual parameter that defines the initiation of the stepping action is the angle between the line from the tip of the foot to the bottom of the step and the line from the tip of the foot to the top of the step. These authors showed that different groups of perceivers with regular visual perception initiated the stepping action when this angle reached the value of 68.3°, which is to say, when the height of the riser was 2.5 times the distance to the step. Such findings, related to the informational basis of actions, may have important implications for the design of SSDs: If one aims to facilitate the control of the stepping action it may be crucial to design SSDs that allow the detection of the angle considered by Cesari et al. An example of an SSD designed for stepping on obstacles—although not inspired by the results of Cesari et al.—can be found in Lobo et al. (2014).

To summarize, we believe that basing further work with SSDs on the conceptual background of the ecological approach to perception, which includes the notion of affordances, may improve both the usability of the devices and the scientific knowledge of the involved perceptual and behavioral processes.

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Chapter 5

Sensory Substitution: Using a Vibrotactile Device to Orient and Walk to Targets

Sensory[1] Substitution Devices (SSDs) aim to substitute one sensory modality through another one. This study investigates how active exploration helps users of SSDs to detect information that is specific to relevant environmental properties. A vibrotactile SSD was developed that generates stimulation contingent on users' movements. Target direction was specified by the location of vibration and target distance by the size and the intensity of vibration. A series of experiments was performed with blindfolded participants. In Experiments 1a to 1c, participants used the SSD to align their central body axis with pre-specified targets. These experiments differed in the number of actuators that were used and whether on-line perception-action coupling was present. In Experiment 2, participants approached targets with forward locomotion along a straight line. Experiment 3 combined the previous experiments and studied the concomitant walking and steering toward targets.

Oscillatory movements were observed in all experiments. The exploratory oscillations were shown to depend on the on-line perception-action coupling and they were related to cases of hyperacuity: Absolute errors smaller than the areas

[1] This chapter is submitted with the next reference: Lobo, L., Travieso, D., Jacobs, D. M., Rodger, M., & Craig, C. M. (2017). *Sensory Substitution: Using a Vibrotactile Device to Orient and Walk to Targets.* Manuscript submitted for publication.

of sensitivity of the actuators. It is concluded that future research on sensory substitution should pay more attention to active exploration and the detection of action-relevant information.

5.1 Introduction

The idea of using one sensory modality as a substitute for another modality is not new. Since the early sixties, the popularity of developing and testing devices that use alternative forms of sensory information has grown. As an illustration of this growth, a recent Google Scholar search using the term *sensory substitution* over the five decades between 1960 and 2009 yielded 13, 198, 373, 615, and 2570 hits per decade, respectively, and 4140 hits since 2010[2]. Reviews of different Sensory Substitution Devices (SSDs) include the ones by Jones and Sarter (2008), Dakopoulos and Bourbakis (2010), and Visell (2009). As can be noted in these reviews, SSDs are potentially useful in a wide range of situations. Vibrotactile SSDs, for example, may be useful in situations in which vision is not available, or less available, due to, say, smoke in the case of fire fighters, weather conditions in the case of pilots, or biological damage in the case of visually impaired users (Carton & Dunne, 2013; Cholewiak & Collins, 2000).

The number of potential users of SSDs is large. In 2010, the estimated number of people with visual impairment was 285 million, 39 million of whom were estimated to be blind (Pascolini & Mariotti, 2011). Compared to the number of possible users, the number of SSDs that are available on the market and/or that are actually being used is low (Lenay et al., 2003). The apparent shortage of SSDs is indicative of the unsatisfactory aid that these devices offer in everyday tasks (Durette et al., 2008; Hersh & Johnson, 2008; Lobo et al., 2014). The overall purpose of our research project is to improve the understanding of why SSDs tend to be unsatisfactory in everyday life. Our hope is that by improving this understanding, we contribute to improvements in the theoretical grounding of future SSDs and, thereby, to the applicability of SSDs. To anticipate, we believe that the functioning of SSDs can be improved by focusing on the specificational nature of the information delivered to users and on the active detection of that information.

[2]Search performed on January 24, 2017.

Before we address these issues, we address several reasons that have previously been suggested for the limited use of SSDs by visually impaired users.

Prominent examples of SSDs from the 1960s and 1970s include the Optohapt (Geldard, 1960), the Optacon (Craig, 1976; Linvill & Bliss, 1966), and the TVSS (Bach-y-Rita et al., 1969). These SSDs stimulated the skin on the fingertips, points distributed over the body, and the back, respectively. Initial results with these SSDs were promising and the researchers were optimistic concerning the role of the skin as a suitable sensory surface for sensory substitution. In later decades, there was a belief that using more sensitive receptor areas would lead to more effective SSDs. This belief led to the development of devices such as the TDU (Tongue Display Unit), which applies electrotactile stimulation to the tongue (Bach-y-Rita, Tyler, & Kaczmarek, 2003). Even highly sensitive receptor surfaces such as the tongue, however, are not nearly as sensitive as the eyes. This fact is nicely illustrated by a study of Sampaio, Maris, and Bach-y-Rita (2001). These authors used the Snellen tumbling E, typically used to test visual acuity, to quantify the acuity of trained TDU users. The 50% correct-response level for the TDU users was observed at a 20/240 Snellen ratio. In the US, individuals with such acuity values for vision would be considered legally blind. A first reason that has been suggested for the unsatisfactory performance of SSDs in everyday life, therefore, is that the sensitivity of the used receptor surfaces may be insufficient.

In addition to the limited sensitivity of the receptor surfaces themselves, the usability of SSDs may be restricted by the cognitive processing capabilities associated with the receptor surfaces (Gallace, Tan, & Spence, 2007; Loomis et al., 2012; Spence, 2014). Spence (2014), for example, argued that cortical plasticity is not sufficient to overcome the processing limitations associated with tactile stimuli. According to Spence, such limitations make it unlikely that users of tactile SSDs can cope with the high spatiotemporal variation of the stimulation that is required to substitute the general function that regular vision plays in our everyday life. Hence, a second reason for the unsatisfying usability of SSDs may be a limitation in cognitive processing capabilities for information presented via the skin as compared to the cognitive processing capabilities for visually detected information.

We believe, however, that the above-reviewed reasons are not as crucial as has previously been argued. A third possible reason for the less than expected applicability of SSDs may be that the design of the SSDs does not sufficiently take into account what information is used, how this information specifies task-relevant properties, and how exploratory actions allow for the detection of the information (Jansson, 1983; Lenay et al., 2003; cf., Guarniero, 1974). This third reason is consistent with the results of a substantial number of studies that show how SSDs that allow for the active detection of relevant information leads to reasonably accurate performance (Auvray et al., 2007; Bermejo et al., 2015; Díaz et al., 2012; Faugloire & Lejeune, 2014; Favela et al., 2014; Ito et al., 2012; Lobo et al., 2014; Travieso, Gómez-Jordana, Díaz, Lobo, & Jacobs, 2015). Let us describe one of these studies.

Díaz et al. (2012) explicitly focused on the role of active exploration in sensory substitution. The tested SSD consisted of a vertical array of 24 actuators on the torso, which vibrated as a function of distance. If a user of the device stood straight up in front of a flat ground surface, all actuators vibrated with the same low intensity. The activation pattern changed whenever the relation between the user and the environment changed, either due to movements by the user or due to the presence of an obstacle on the ground surface (see Figure 1 of Díaz et al.). In their first experiment, Díaz et al. showed that the threshold for the detection of obstacles with the SSD is lower for a use with exploratory movements than for a use without such movements. The exploratory movements typically consisted of forward and backward walking and/or tilting the upper body. In their second and third experiments, dynamic groups that received vibrotactile stimulation generated on-line by their own exploratory movements had lower detection thresholds than yoked groups that received stimulation corresponding to previously registered exploratory movements. This demonstrates that, for an optimal performance, the vibrotactile stimulation provided by SSDs should be contingent on the user's movements.

Although Díaz et al. (2012) demonstrated the importance of active exploration with action-contingent vibrotactile flow, they did not analyze the exploratory movements themselves. The present study further investigates active exploration and information use in sensory substitution, using a different experimental framework: spatial orientation and locomotion. We believe that this is an appropriate framework. First, orientation and locomotion are important for people with and without visual impairment. Second, the framework entails real-world tasks that allow scientists to test SSDs and to quantify performance. As argued by Faugloire and Lejeune (2014), a majority of the studies with SSDs on the tactile guidance of movement do not report complete quantitative measures of performance. For example, the reported measures may be limited to the time that users take to complete the task, without quantifying errors in performance. Third, visually guided locomotion toward targets has been studied extensively. This has led to rich knowledge about the operative information (e.g., Bastin, Craig, & Montagne, 2006; Morice, François, Jacobs, & Montagne, 2010). It may be fruitful to relate research on sensory substitution to the previous knowledge about the information that is used for the visual guidance of locomotion.

An elegant experimental paradigm to study visually guided locomotion has been proposed by Fajen and Warren (2003; cf. Fajen, Warren, Temizer, and Kaelbling, 2003). The experiments reported in that study were performed in a large virtual environment, in which targets and obstacles could appear in the form of vertical cylinders. In Experiment 1, Fajen and Warren used targets placed at different initial distances and angles, while in Experiments 2 and 3 both targets and obstacles were used. Participants, who had a 60°-wide field of view, were asked to walk toward the targets and to avoid obstacles. Fajen and Warren also proposed a model, which describes steering behavior with dynamic terms for the targets (attractors) and obstacles (repellers). Arguably, the main contribution of Fajen and Warren's study is the demonstration that route selection can emerge from an online coupling of action to simple optical variables, making explicit route selection and planning unnecessary. The most relevant result for us, at this point at least, is that locomotion toward a target was shown to be based on the body-referenced direction to the target and the distance of the target. We use θ to refer to the body-referenced direction of the target (Bootsma & Craig, 2002; Bastin, Jacobs, Morice, Craig, & Montagne, 2008).[3]

To summarize, visually guided locomotion can be characterized as an online information-action coupling. Our approach to sensory substitution also gives a prominent role to information-action coupling. The purpose of our study is twofold. First, we investigate the movements that underlie active information detection with a vibrotactile SSD. Second, we aim to illustrate the suggested benefits in performance when SSD-based perception is conceived as active information detection.

[3]Multiple θ-like variables have been claimed to be relevant for the visual guidance of movement (Craig et al., 2009; Michaels, Jacobs, & Bongers, 2006). Several of these variables are easily confused with θ as defined by us, including the direction of the target with respect to a fixed reference frame or with respect to the movement direction of observers (rather than with respect to body orientation).

We designed an SSD that allows for the detection, through vibrotactile stimulation on the abdomen, of the information that has been shown to be used in visually guided locomotion (Fajen & Warren, 2003). The body-referenced direction of the target, θ, is indicated by the location of the vibration (e.g., van Erp et al., 2005), and the distance to the target is indicated by the intensity and size of the stimulation (Cancar et al., 2013). In the remaining part of this article, we describe the SSD, indicate how it presents the information to the user, and report on three experiments that assess how users actively detect and use this information to navigate in an environment without sight of the target.

In Experiments 1 and 2, we separated out the information that would specify orientation from the information that specifies distance. Experiments 1a to 1c, similar to Faugloire and Lejeune (2014), focused on orientation of the mid-line of the torso with respect to a virtual target. Participants were presented with information that indicated where the target was located with respect to the torso mid-line. Experiment 2 concerned targets located directly in front of the participants. In this case, the vibrotactile stimulation specified the distance the target was away from the participant. The task used in Experiment 3 was a combination of the tasks used in the previous experiments: Participants walked toward targets located at different angles and distances in front of them. Experiment 3 hence was a vibrotactile version of the first experiment by Fajen and Warren (2003).

5.2 General Method

5.2.1 Ethics Statement

This research project was approved by the respective research ethics committees of the Queen's University of Belfast and the Universidad Autónoma de Madrid. Written informed consent was obtained from all participants.

5.2.2 Apparatus

The SSD used in this research consisted of an elastic band (95 × 16 cm) with 72 vibrotactile actuators attached to it in an area of 40 × 12 cm (Figure 5.1). The actuators were coin motors with a diameter of 12 mm and a height of 3.4 mm. The motors were organized in three rows of 24; the horizontal distance between the actuators was approximately 1.7 cm. The elastic band was placed on the abdomen. The tactile information presented through the SSD specified the distance between the participant and the target (i.e., vibration intensity and number of actuators activated) and the angle between the person and the target (i.e., the relative location of active actuators). The data that corresponded to the participant's actual position were generated from the motion capture system and were incorporated into a software program to calculate in real time the angle and the distance between the participant and the target. This information was converted into a signal that stimulated the appropriate actuators. The actuators were controlled by a Pro-mini arduino microcontroller that received the signal through a wireless Xbee device, model S2. A NiMh Battery of 4000 mA/h supplied the energy for the actuators. The battery and microcontroller were housed inside a backpack: The SSD was completely portable.

The position and orientation of the participant were measured using a passive infrared motion capture system (Qualisys AB, Sweden). A system with Oqus cameras (10 in Experiments 1a, 2, and 3; 6 in Experiments 1b and 1c) recorded the position of five reflective markers attached to the SSD, at 100 Hz. Given that the vibration of the actuators depended on the position and orientation of the participant with respect to the predefined virtual target, the voltage level required to create the necessary vibrations was computed on-line. These computations were updated approximately 43 times a second.

5.2.3 Procedure

Prior to the experiments, verbal instructions were given to participants along with a demonstration and explanation. The information provided was: "We have developed a new tactile device for people who are visually-impaired. With this device you will receive tactile stimulation on your abdomen that should help you locate and move toward a target in this room. The device has 72 small motors attached to a large elastic band that will be placed on your abdomen. You will feel different levels of vibration that will indicate how close you are to the target and whether you are walking directly toward the target. The more intense the vibration of an

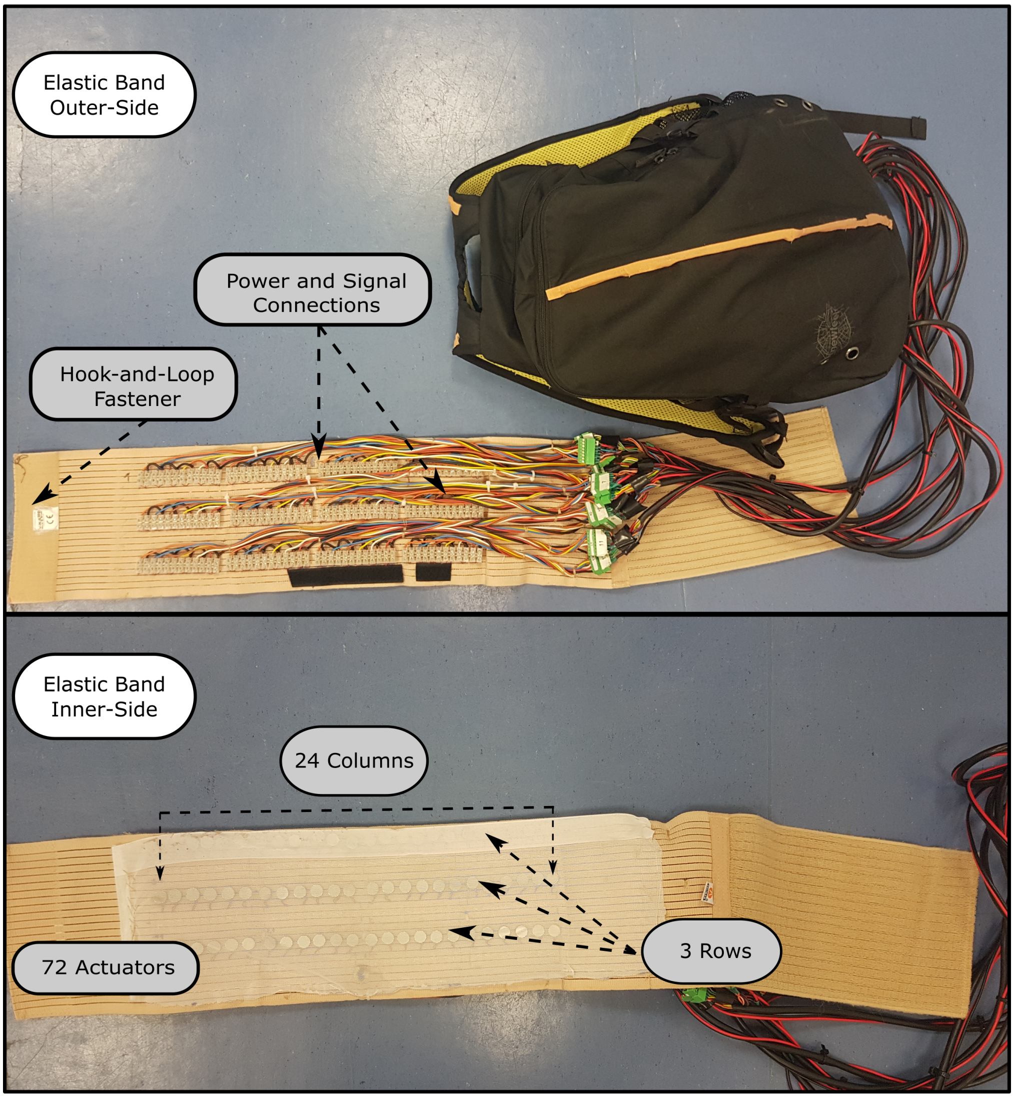


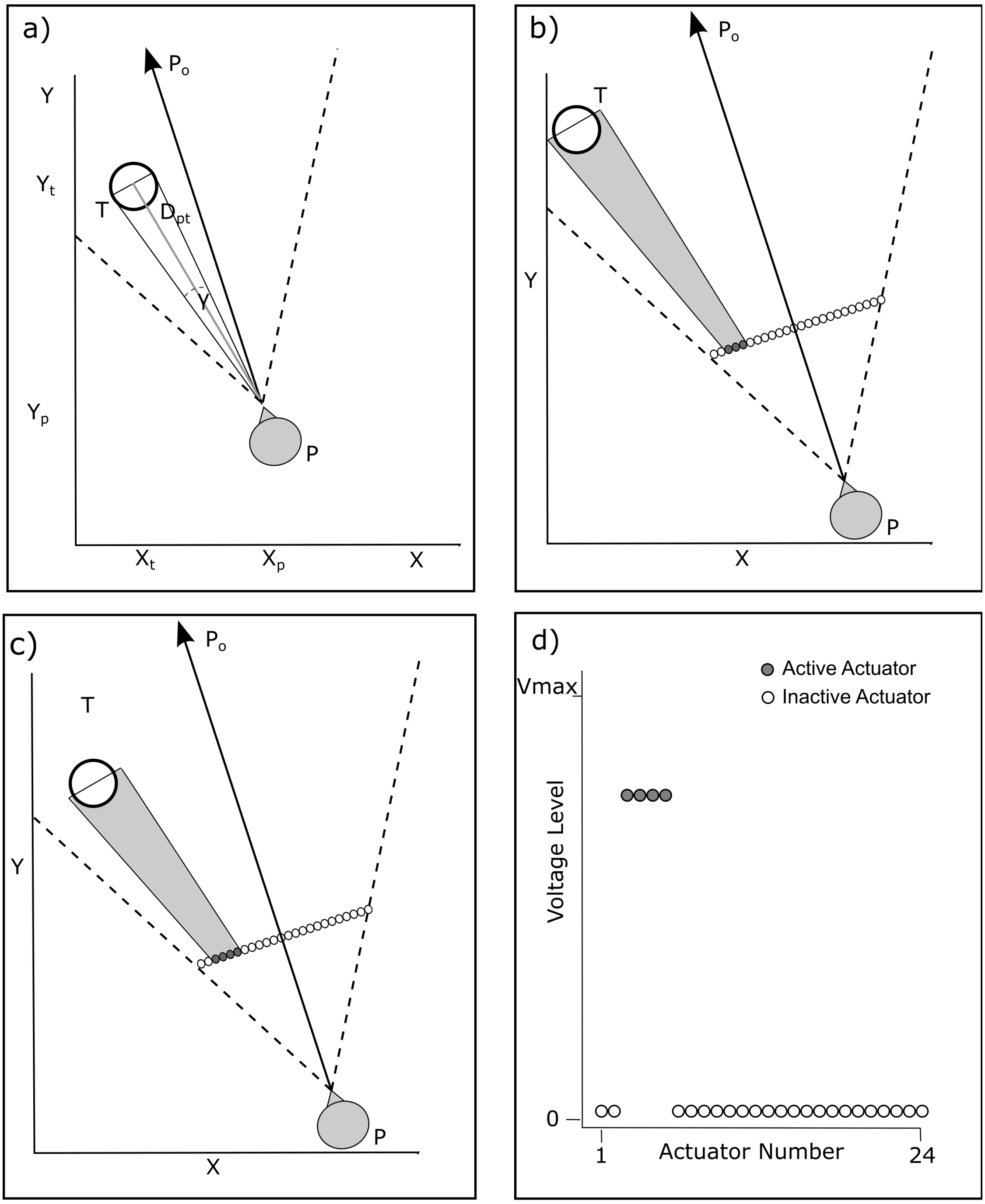
Figure 5.1: Picture of the SSD used in the experiments.

individual motor, the closer you are to the target with the inverse also being true (that is, the less intense the vibration, the further away you are from a target). Equally, the greater the number of motors that are active and vibrating, the closer you are to the target; with fewer motors vibrating indicating that you are further away. The motors also vibrate at different positions on the band, which correspond to the location of the target. For example, if the motors on your right hand side vibrate, then the target is located on your right. As you turn your body toward the target on the right, the pattern of vibration of the motors will move toward the center. When the vibration is located in the center, this indicates that the target is straight ahead." After this explanation, the participants were blindfolded and were offered the opportunity of exploring the surface of the SSD with their hands. Subsequently, the experimenter placed the part of the SSD with the actuators on the abdomen. Participants remained blindfolded.

5.2.4 Activation Level of Actuators

The three actuators arranged in a vertical line always had the same level of activation. If they were activated, the intensity of the vibration was a function of the distance between the participant and the target, following the equation: $V = V_{max} - c \times D_{pt}$, where V is the voltage level expressed as a percentage of the maximal voltage level V_{max}, D_{pt} the distance between the participant and target in centimeters, and c a constant that maintains the vibration intensity in a useful range. The voltage level V_{max} corresponded to an estimated frequency of the actuators of about 65 Hz (see Appendix A of Díaz et al., 2012). In the experiments, c was set at 0.12. This means, for example, that when D_{pt} was 100 cm, the voltage level was 88% of V_{max}. The voltage level was set at zero whenever, according to the equation, it should have been negative. Actuators worked like virtual sensors. They were activated when they detected the virtual target in their (vibrotactile) field of view. The targets were virtual in the sense that, although they determined the vibration patterns of the SSD, they did not exist as real objects in the experimental set up. Actuators were turned off when the virtual target went outside their field of view. The total field of view of the SSD was set at 60°. This was motivated by the 60° visual field of view in the experiments of Fajen and Warren (2003). The total field of view was divided in 24 units of 2.50°, corresponding to the fields of view of each of the 24 columns of actuators. Thus, the leftmost actuators in the device detected targets when these were located in the range between 30° to 27.5° to the left of the body axis, the second column of actuators detected targets between 27.5° to 25° to the left, and so forth, until the rightmost column of actuators that detected targets in a range between 27.5° to 30° to the right of the body axis. All fields of sensitivity were computed from the same central position on the body. Hence, the position and orientation used to compute the activation levels did not exactly match the position and orientation of the actuator on the body.

Figure 5.2 provides an example that shows how the SSD functions. If we establish the participant's orientation as being P_o (measured using the motion capture system), the SSD takes into account a field of view that corresponds to 30° on either side of P_o (see dashed lines in the figure). The virtual target T has a fixed diameter of 20 cm that occupies a vibrotactile angle γ, which depends on the distance D_{pt} between the participant and the target (Figure 5.2a). The angle γ, in turn, determines the number of actuators that detect the target (i.e., actuators



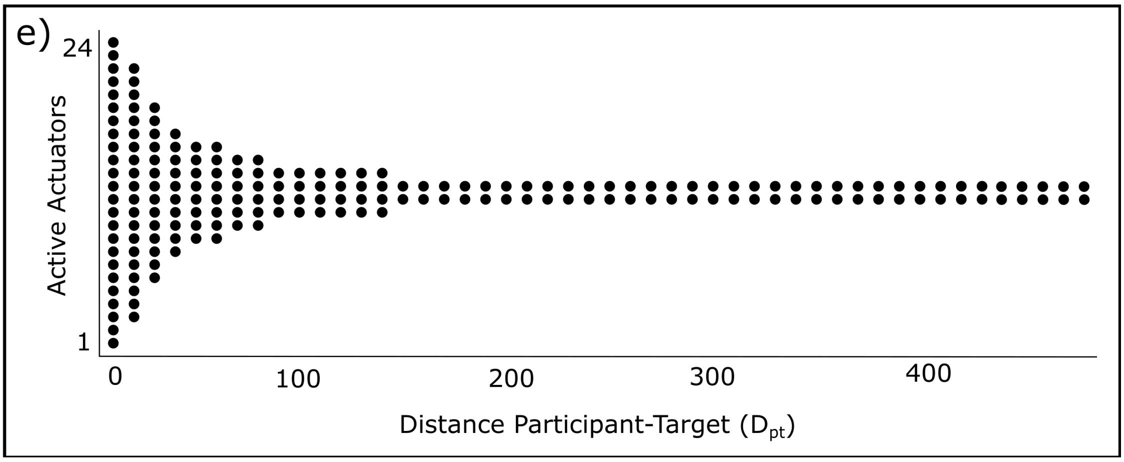


Figure 5.2: (a) Participant, P, with a heading direction, P_o, and a target, T, placed at a distance, D_{pt}, that occupies a certain angle, γ. Dashed lines represent the field of view of the SSD. (b) Three actuators are marked in grey, representing the actuators that are active in the situation depicted in (a); open circles represent actuators that are not active. (c) As the participant approaches the target, the number of active actuators increases to four. (d) Voltage level of the actuators in the situation depicted in (c). (e) Actuators that are turned on and off as a function of D_{pt}. The shown pattern corresponds to a participant that increases the distance to a target located straight ahead. The figure provides a top view: Each circle in the figure represents a horizontal column of three (equally vibrating) actuators in the actual device.

that have the target in their field of view; Figure 5.2b). When the distance D_{pt} reduces, the angle γ increases, and, as a consequence, the number of active actuators increases (Figures 5.2b-2c). To facilitate the illustration, the actuators in Figures 5.2b and 5.2c are depicted on a straight line before the body; in the experiments the actuators were placed on the body. Figure 5.2d shows the results of applying the above-mentioned equation to determine the intensity of vibration to the situation depicted in Figure 5.2c. Figure 5.2e indicates the actuators that are active as a function of distance, for a target that is approached straight ahead.

5.2.5 Data Analysis

Using the data recorded with the motion capture system, we carried out several analyses on performance and movement variables. A mean of 0.5% of the frames per trial were not properly registered. To fill the gaps in trials with missing frames we used the linear interpolation function *extrap* in Matlab (Mathworks, Inc.). The data were filtered with a forward and backward fourth-order low-pass Butterworth filter with a cut-off frequency of 12 Hz. We computed errors in performance as the difference between the target location and the participant's position or orientation at the end of the trial. We measured these differences as real values (signed errors) and absolute values (magnitude of errors). When performance referred to target location behaviors, the sign of the error was negative when the final position was before the target (undershoot) and positive when the final position was after the target (overshoot). When performance referred to the orientation of heading, the sign of the error was positive when the final heading position was to the right of the target and negative when it was to the left of the target. The maxima and minima in the time-series of the angle θ were determined and used to compute the number of oscillations. An oscillation was defined as a full cycle from a maximum to a minimum and back to a maximum; which is to say, a change from a maximum to a minimum or vice versa counted as a half oscillation. Huynh-Feldt corrections were applied in the case of the rejection of the sphericity assumption in repeated-measures ANOVAs. Welch ANOVAs were applied in the case of rejection of homogeneity of variances in one-way ANOVAs. In those cases, Games-Howell tests were applied instead of Tukey's HSD post hoc comparisons.

5.3 Experiment 1a: Orienting the Body Axis to Targets

The present series of experiments on SSD-based locomotion uses an experimental paradigm that has previously been used to study visually controlled locomotion (Fajen & Warren, 2003). The task studied by Fajen and Warren implies forward locomotion as well as turning. As a first step toward the application of this task in sensory substitution, our Experiments 1a to 1c addressed the capacity of participants to use an SSD to turn their anterior-posterior body axis toward targets.

Whereas Experiment 1a used the SSD with its full functionality, Experiments 1b and 1c did not: in Experiment 1b we removed the on-line perception-action coupling and in Experiment 1c we reduced the number of actuators.

Previous work in the field of sensory substitution that used this task includes the study by Faugloire and Lejeune (2014; cf. Tsukada and Yasumura, 2004). The SSD of Faugloire and Lejeune had eight vibrotactile actuators placed around the abdomen. As in our Experiments 1a to 1c, participants were asked to rotate toward the direction indicated by the vibration. The experiment of Faugloire and Lejeune included conditions with fast (200 ms on / 200 ms off) and slow (1 s on / 4 s off) vibration rhythms, for which average absolute errors of about 10° and 15° were observed, respectively. Let us emphasize two interesting aspects of these results. First, the errors were smaller than the area of sensitivity of the individual actuators (which was 45°). Second, the faster rhythm led to better performance. In line with the arguments outlined in our introduction, according to Faugloire and Lejeune the faster rhythm is more beneficial because a more direct coupling of the stimulation to the user's actions allows for an active search to pick up and use goal-relevant information.

Our Experiment 1a differed in two crucial aspects from the one by Faugloire and Lejeune (2014). First, we used 3 rows of 24 actuators placed on the front of the abdomen, whereas Faugloire and Lejeune used eight actuators placed around the full 360° of body. Relatedly, the area of sensitivity of each actuator in our study was 2.50° while it was 45° in the study of Faugloire and Lejeune. Second, the activation was updated with a frequency of 43 Hz, rather than in rhythms with 2.5 (or fewer) bursts per second. Updating the vibration frequency with 43 Hz means the vibration had no off phases: The vibration was present whenever the target fell within the field of view of the SSD.

5.3.1 Method

Seven women and four men ($M_{age} = 27.6$, $SD = 4.4$) who were students or members of university staff at the Queen's University of Belfast participated in the experiment. None of them had previous experience with SSDs. All participants had normal or corrected-to-normal vision. Participants were asked to rotate their body about the longitudinal axis in order to face a virtual target. The vibration provided by the SSD was adapted on-line using the information specifying the angular direction of the virtual target with respect to the participant. The distance between the participant and the target (D_{pt}) was fixed at 200 cm. This resulted in a constant angle θ of 5.72° (Figure 5.2a) and a constant intensity of vibration. Which actuators were activated depended on the participant's orientation with respect to the target. If the participant changed his or her orientation, the actuators that were activated would change accordingly. For example, if the target and the participant were perfectly aligned, the vibration would be at the body's center, but if the center of the torso was oriented to the left of the target, then the actuators on the right part of the abdomen would be activated.

Participants completed three familiarization trials with the following target locations: -30°, 0°, and 30°. After the familiarization trials, participants started the test trials. Six locations with respect to the center (0°) were used for the test trials: ±5, ±15, and ±25° (Figure 5.3) each being repeated 3 times (18 trials in total)[4]. The trials were presented in quasi-random sequences that were chosen so that participants, if performing perfectly, did not have to rotate more than 40° between consecutive trials. Participants indicated verbally when they believed that a correct alignment was achieved, upon which the experimenter ended the trial. The duration of the experiment was approximately 15 min.

5.3.2 Results

Overall description of performance.

All participants reported that the use of the SSD in this experiment was intuitive and simple. Four trials (2.0% of the total number of trials) were not properly recorded and were discarded from the analyses. Two further trials were not correctly recorded at the moment of the decision; the error and position variables from these trials were not included in the analysis. At the start of a trial, participants

[4]Due to programming error, targets with a smaller x coordinate than the participant were displaced to the left with an angle that was identical to γ. The same programming error was present in Experiment 3. We believe that this error did not have any effect on the results of Experiment 1a and that, if anything, without this error the results of Experiment 3 might have been slightly more favorable with respect to the usefulness of the device.

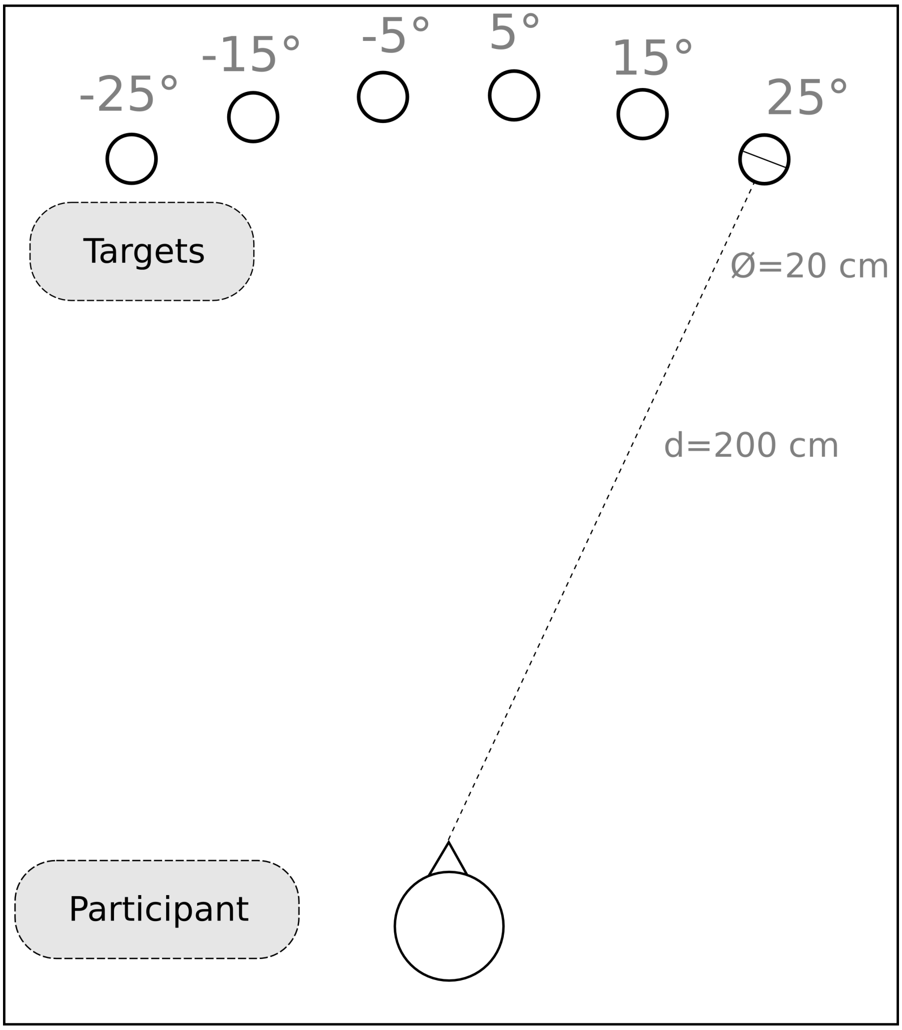


Figure 5.3: Schematic representation of the location of targets in Experiment 1. The distance between the participant and the targets was fixed at 200 cm. ∅ is the target diameter.

almost always started to turn their upper body to one side and then to the other. These sweeping movements of the upper-body sometimes involved slight movement of the feet. The upper-body movements were repeated with decreasing amplitudes until participants stopped and announced that they had made a decision (Figure 5.4a).

Heading direction.

Three ANOVAs were performed with target location as the within-subjects factor. The first ANOVA examined the final heading direction of participants. A strong

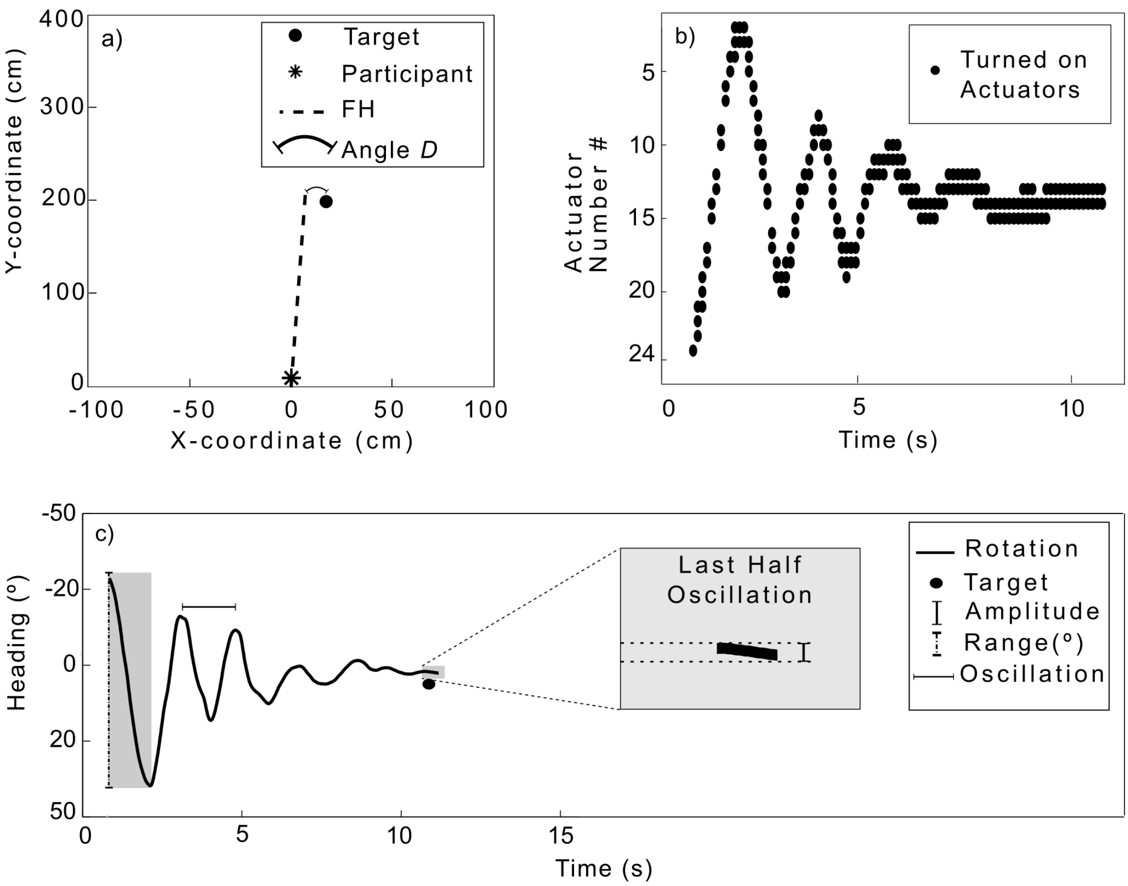


Figure 5.4: Example of a trial from Experiment 1 with a target located at 5°. (a) Heading direction at the last frame of the trial (FH = Final Heading). (b) Vibration patterns provided by the SSD during the trial. (c) Rotational movement during the trial, with an enlargement of the last oscillation shown in the grey square. Range = maximum angular space explored during the trial; Amplitude = Amplitude of last half oscillation.

significant effect of target location was observed, $F(4.1, 114.3) = 5042.1$, $p < .001$, $\eta_p^2 = .99$. This demonstrates that the participants' final heading was a function of the actual target locations, and hence that the SSD allowed participants to distinguish the targets.

Signed angular deviation.

The second ANOVA was performed on the signed errors, computed with the angle D in Figure 5.4a. This ANOVA did not reveal a significant effect of target location, $F(3.9, 100.6) = 0.6$, $p = .65$, $\eta_p^2 = .02$. Hence, in contrast to studies that showed larger errors for the outer targets when pointing in the absence of visual information (Adamovich, Berkinblit, Fookson, & Poizner, 1998; Craig & Bourdin, 2002), we did not observe such differences. The average signed deviation was -0.2° (*SD* = 1.8). The signed deviation was not significantly different from the angle $D = 0°$, t (191) = -1.6, $p = .11$. Hence, at the moment of the decision, the variability of heading was approximately equally distributed to the left and right of the targets.

Absolute angular deviation.

The ANOVA on the magnitude of the errors, also computed using the angle D, did not reveal a significant effect either, $F(3.9,\ 100.8) = 0.4$, $p = .77$, $\eta_p^2 = .01$. The average magnitude was 1.4° (*SD* = 1.1). This mean is lower than the angle of sensitivity of a single actuator (2.50°). In fact, the magnitude of the deviation was not significantly different from half of the sensitivity of a single actuator (1.25°), $t(191) = 1.5$, $p = .11$.

Trial duration.

The mean duration of the trials was 7.2 s (*SD* = 2.9). As evidenced by the low correlation between the magnitude of deviation and trial duration ($r[190] = .11$, $p = .15$), the trial duration was not related to the accuracy of the orientation.

Movement variables: Number and amplitude of oscillations.

On average, participants oscillated 3.1 times per trial (*SD* = 1.7). Several oscillatory movements were observed in most of the trials: Only 5.1% of trials showed a single oscillation. Three or more oscillations were seen in 47.4% of the trials. The mean angular velocity was 11.8 deg/s (*SD* = 5.42). The mean angular range, defined as the maximum minus the minimum heading direction in a trial (Figure 5.4c), was 44.4° (*SD* = 20.7). The cumulative angular distance covered by the oscillatory movements was, on average, 86.7° (*SD* = 56.4). The average amplitude of the oscillations was 14.0° (*SD* = 16.7). The amplitude of the last half oscillation before a decision was made was 6.8° (*SD* = 6.8; Figure 5.4b).

5.3.3 Discussion

The present experiment showed that blindfolded users of the SSD performed more than one oscillatory trunk movement in 94.9% of the trials. The amplitude of the exploratory trunk movements decreased over cycles. The final direction of the torso closely corresponded to the direction of the target: The average absolute error was 1.4°. This deviation is below the angular area of sensitivity of each actuator of 2.50°.

The absolute errors in the present experiment are substantially smaller than the absolute errors of about 10° to 15° reported by Faugloire and Lejeune (2014). The more accurate performance in our experiment may be related to the higher number of actuators on our SSD: It is to be expected that a device with areas of sensitivity of the individual actuators of 2.50° allows more accurate orientation than a device with areas of sensitivity of 45° per actuator. In addition, the high accuracy may be related to the absence of off phases in the vibration and the update frequency of about 43 Hz. This almost immediate perception-action coupling may have enhanced the usefulness of the oscillatory trunk movements.

Despite the above-mentioned experimental differences, our main conclusion is consistent with the findings of Faugloire and Lejeune (2014). Faugloire and Lejeune argued that the better performance in the condition with a faster on/off rhythm, compared to the condition with the slower on/off rhythm, was due to the more active search for information facilitated by the more direct perception-action coupling. It may also be interesting to note that the trial duration was longer in our experiment (7.2 s) than in the experiment reported by Faugloire and Lejeune (2.9 s). This difference may be attributed to the more extended exploration in our experiment.

5.4 Experiment 1b: Orienting Without Perception-Action Coupling

Participants in Experiment 1b received vibratory information concerning the direction of the target while standing still. They were asked to turn their body axis in the direction of the target after the vibration had ended. This means that the task was performed without on-line perception-action coupling. We hypothesize that, as compared to Experiment 1a, less exploratory oscillations will be observed in Experiment 1b, and that this reduction will go together with larger absolute errors and shorter trial durations.

5.4.1 Method

Experiment 1b was identical to Experiment 1a with the following exceptions. Twelve students at the Universidad Autónoma de Madrid participated in the experiment (10 women and 2 men; M_{age} = 29.0, SD = 9.8). No on-line perception-action coupling was used. Instead, in all trials, including the familiarization trials, the vibration remained stable with regard to the body during a 7.2-s period in which participants were asked not to move. The used duration corresponds to the average trial duration in Experiment 1a. When the vibration had ended, participants turned their body axis so as to align it with the direction of the target. Before the following trial, the experimenter directed participants back to the original orientation. The size of the body at the level of the SSD along the lateral and antero-posterior axes was measured and used to compute the directions of the used actuators with regard to the midpoint of the body, assuming the shape of the body to be elliptical (Faugloire & Lejeune, 2014). These individually computed reference directions of the actuators were used in the error analyses of this experiment.

5.4.2 Results

The average signed deviation between the direction of the vibration with respect to the body and the final heading of participants was -0.3° (SD = 17.3). The magnitude of the deviation was 12.4° (SD = 11.7). The trial duration was 5.1 s (SD = 1.9). The number of oscillations per trial was 1.9 (SD = 1.1). The average amplitude of the oscillations was 13.3° (SD = 21.9). T-tests showed that the participant means of these measures differed significantly from those observed in Experiment 1a ($ps < .005$), with the exception of the signed deviation and the amplitude of oscillation ($ps > .63$). Specifically, when on-line perception-action coupling was prohibited in Experiment 1b, the absolute angular deviation was greater, the trial duration shorter, and the number of oscillations fewer.

5.4.3 Discussion

The present experiment demonstrates that the accuracy that was observed in Experiment 1a is at least partly due to the on-line perception-action coupling. The finding that the number of oscillations is reduced in the absence of such a coupling indicates the importance of this coupling to facilitate the exploratory behavior that appears to improve performance accuracy. The exploratory oscillations were also shown to have a cost: In Experiment 1b, with fewer oscillations per trial, participants reached their decisions sooner.

5.5 Experiment 1c: Orienting With Few Actuators

In Experiment 1a we observed highly accurate performance using an SSD with 24 columns of actuators that had a field of sensitivity of 2.50° each. Experiment 1c tests the extent to which the number of actuators and the associated fields of sensitivity contribute to the observed performance. As did Faugloire and Lejeune (2014), we used actuators that had a field of sensitivity of 45°. Whereas Faugloire and Lejeune used eight actuators, covering the full 360° circumference of the body, we used three columns of actuators, giving rise to a total field of view of 135°. The columns of actuators that were used were the one on the body midline and two columns located on the left and right.

We hypothesize that, due to the lower resolution of the sensory information, larger errors will be observed in this experiment compared to Experiment 1a. Predictions concerning the exploratory oscillations are less straightforward. With an area of sensitivity of 45°, the majority of the oscillations observed in Experiment 1a would fall within the field of sensitivity of the central actuators and, therefore, they would not lead to changes in the activation of the actuators. Given this, oscillations below a certain amplitude would not be useful, and participants may reduce the number and the amplitude of the oscillations. On the other hand, participants may also increase the amplitude of the oscillations so as to make it more likely to stimulate the actuators on the sides of the SSD (i.e., explore the extreme positions of the device).

5.5.1 Method

Experiment 1c was identical to Experiment 1a with the following exceptions. Twelve students at the Universidad Autónoma de Madrid participated (7 women and 5 men; $M_{age} = 30.6$, $SD = 7.8$). The participants did not participate in other experiments of this study. The elastic band with actuators was placed on the body in such a way that the thirteenth column of actuators from the left was located at the body midline. The columns of actuators that were used in this experiment were Columns 7, 13, and 19 for small participants, Columns 6, 13, and 20 for average-sized, and Columns 5, 13, and 21 for large participants. Independent of the location of these actuators on the body, the center of the fields of sensitivity of these actuators was always directed to -45, 0, and 45°.

5.5.2 Results

The average signed deviation was 0.5° ($SD = 14.4$). The magnitude of the deviation was 12.3° ($SD = 7.5$). The trial duration was 8.1 s ($SD = 3.5$). The number of oscillations per trial was 2.8 ($SD = 1.6$). The average amplitude of the oscillations was 14.0° ($SD = 18.8$). Table 5.1 shows the averaged absolute error, trial duration, and number of oscillations, for Experiments 1a to 1c. The table indicates that the absolute error was significantly lower in Experiment 1a than in the other two experiments, and that the trial duration and the number of oscillations were significantly lower in Experiment 1b. To further illustrate the differences between the experiments, Figure 5.5 shows that the reduction in the amplitude over cycles was steeper in Experiment 1b, without on-line perception-action coupling, than in Experiments 1a and 1c[5].

[5] Let us also mention that the standard deviations of the amplitudes shown in Figure 5.5 were slightly higher for Experiment 1c than for Experiment 1a for all half cycles. For the last four half cycles shown in the figure, these standard deviations were 12.8, 12.3, 10.4, and 9.0 for Experiment 1a, and 14.9, 18.1, 17.4, and 12.9 for Experiment 1c. In line with our reasoning in the Introduction of Experiment 1c, we believe that this difference is due to the fact that on some occasions the amplitude was reduced because the target remained within the field of sensitivity of the central column of activators, whereas on other occasions the amplitude was increased so as to try to reach the target with the fields of sensitivity of the side actuators.

Table 5.1: Means of Main Dependent Variables in Experiment 1a to 1c With Results of Statistical Comparisons

Dependent Variable	Experiment 1a	Experiment 1b	Experiment 1c
Absolute Error (°)	1.4^a	12.4^b	12.3^b
Trial Duration (s)	7.2^a	5.1^b	8.1^a
Number of Oscillations	3.1^a	1.9^b	2.8^a

Note. One-way ANOVAs with Experiment as between-subjects factor were significant for each of these dependent variables ($Fs > 9.7$, $ps < .001$). The letters that accompany the means indicate the results of post hoc tests: Two means in the same row are significantly different ($p < .01$) only if they have a different letter.

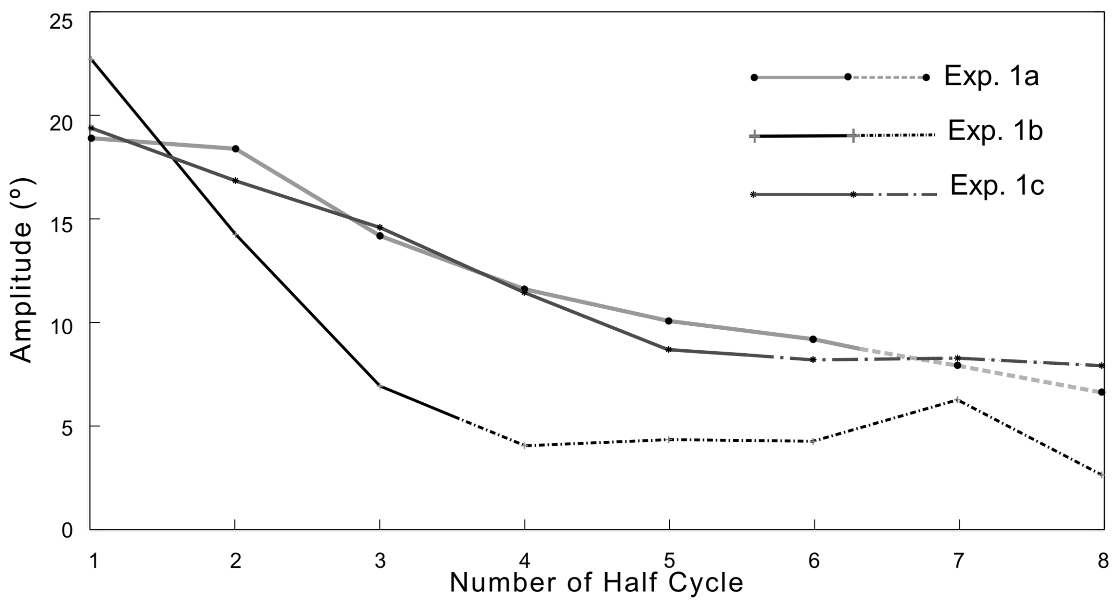


Figure 5.5: Average amplitude per half cycle of the oscillations observed in Experiments 1a to 1c. In all experiments, the amplitudes were large early in the trial and declined later on. The further to the right in the figure, the less observations were available to compute the means. For example, only eight trials in Experiment 1b showed eight half cycles. All other means were based on more trials. Continuous lines indicate that the number of half cycles was still below the average number of half cycles observed in the condition; discontinuous lines indicate that the number of half cycles surpassed the condition average.

5.5.3 Discussion

The present experiment confirmed our main hypothesis: The magnitude of the errors in this experiment was larger than in Experiment 1a. The number of exploratory oscillations was closer to the number observed in Experiment 1a than to Experiment 1b. Hence, with the on-line perception-action coupling present and using actuators with a field of sensitivity of 45º instead of 2.50º, the accuracy of performance was still reduced but not the exploratory behaviors. Taken together, Experiments 1a to 1c demonstrate that, for an accurate orientation performance, a large number of actuators (resolution of the sensory flow field) and a sufficiently direct perception-action coupling are both needed.

5.6 Experiment 2

Experiment 1 addressed orientating the body axis toward the targets. The next step in our study of haptic navigation using an SSD concerns the approach to the target, without turning. Experiment 2 addressed the performance of individuals who, using the SSD, walked toward a virtual object placed a few meters in front of them. To be able to do this, the SSD provided information about the distance between the participant and the target, D_{pt}. This information was simultaneously provided in two ways: through the vibrotactile angle γ and the intensity of vibration (Figure 5.2).

Being able to control the approach to a target while walking is an essential part of spatial navigation with SSDs, but it has rarely been studied in an extensive way. Jansson (1983) used an SSD that provided vibrotactile information to the abdomen of two blind participants and asked them to walk 2 m and then point to a target. Although Jansson reported successful behavior, he did not report measurements concerning the errors in performance. van Erp et al. (2005) addressed the issue of tactile information about distance in a more explicit manner. These authors showed that vibrotactile stimulation applied to the waist allowed participants to successfully locomote along routes indicated by (invisible) waypoints. As mentioned above, the device tested by van Erp et al. indicated the direction of the waypoints by the location of the vibration. Distance was coded by varying the length of the

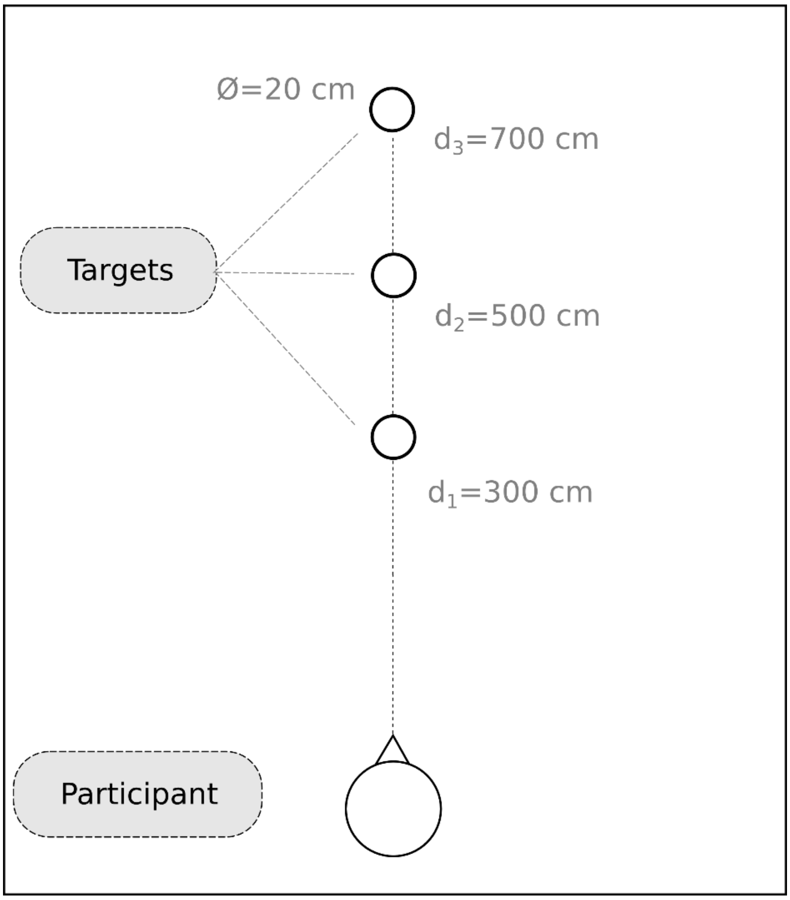


Figure 5.6: Schematic representation of the layout of the targets in Experiment 2. Targets were aligned with the participant's mid-point. Rotational movements were not necessary and therefore not taken into account.

off-phase between vibratory pulses that had a fixed duration of one second. Van Erp et al. reported that the alternative ways to code distance did not lead to significant differences in performance. In fact, not coding distance led to (non-significantly) better performance than any of the tested ways to code distance.

The lack of a performance advantage of the distance information provided in the study by van Erp et al. (2005) may have been due to the reduced benefit of knowing distance in the used task, rather than to the possible difficulty of the participants to detect and use the information. Given that the distance to the target is the only parameter that needs to be controlled by participants in the present experiment, our experiment provides a clearer test of the hypothesis that SSD users are in fact able to take advantage of distance information. In addition, the experiment allows us to test if exploratory oscillations occur also in this task.

5.6.1 Method

This experiment was performed by the same 11 participants as Experiment 1a. If they wanted to, the participants could take a short break between the two experiments. We asked participants to walk in a straight line until they reached the target. In contrast to the previous experiments, in this experiment the SSD provided information about the distance between the participant and the target, D_{pt}, but not about the participant's orientation. Consequently, the vibrotactile angle γ and the intensity of vibration varied normally, but the actuators that were turned on were always the ones in the middle. Participants started each trial from the starting point and they walked toward a virtual target placed at a distance of 300, 500, or 700 cm (Figure 5.6).

The experimenter asked participants to follow a straight line. If participants deviated from that line, the experimenter advised them to turn in the correct direction. If a participant reached the target, the intensity of vibration and the number of vibrating actuators were at the maximum levels allowed by the SSD. If the target was passed, the intensity of vibration diminished as D_{pt} moved away from zero again. Before test trials, participants completed three familiarization trials, with targets located at three distances not used during test trials: 200, 400, and 600 cm. After the familiarization trials, participants performed 3 (distances) $\times$ 5 (repetitions) = 15 experimental trials, presented in a random order. The experiment took approximately 20 min.

5.6.2 Results

Overall description of performance.

On some trials participants walked in a relatively straight line, with some lateral deviations due to body sway, and stopped around the target area. In other trials they passed the target and recovered the position by walking backward (Figure 5.7). In general, participants reported that it was easy to decide where to stop, but that sometimes it was useful to feel how the intensity of vibration and the number of actuators decreased when the target had been overshot. Eight trials (4.8% of the total number of trials) were not properly recorded and were not used in the analyses.

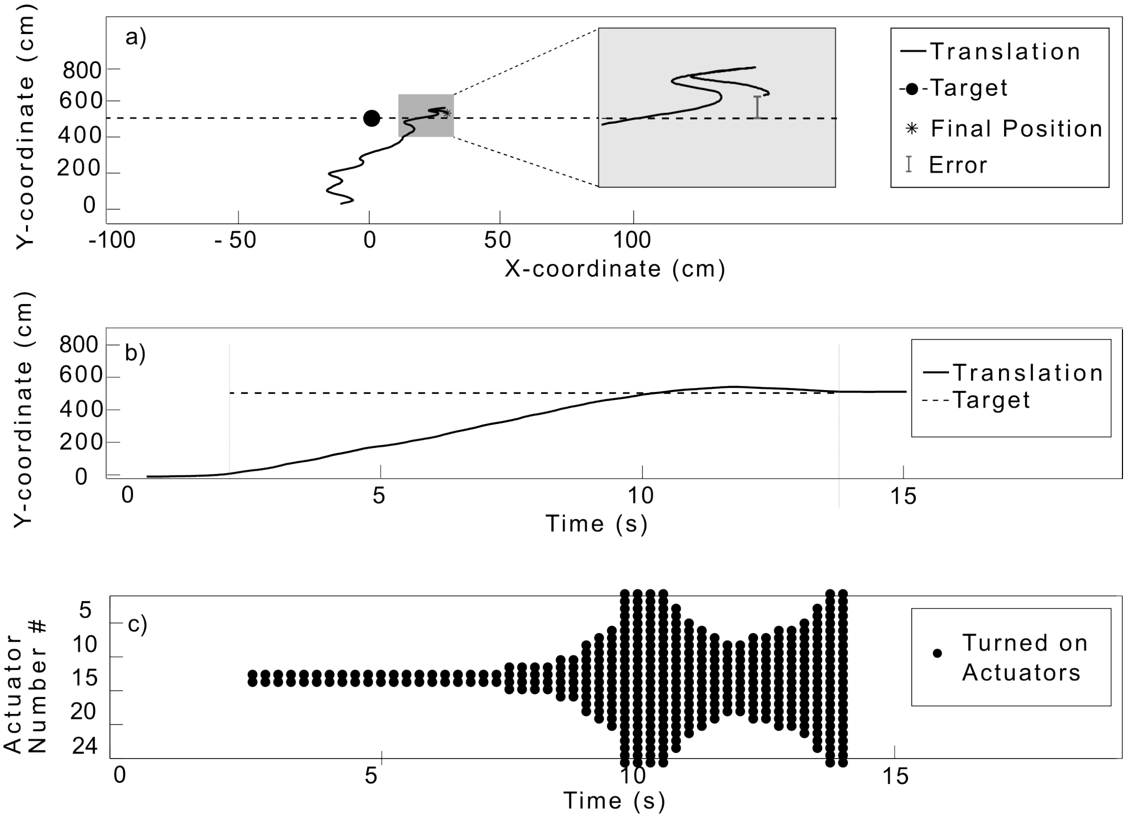


Figure 5.7: Example of a trial from Experiment 2. (a) Participant's approach to the target. The dashed line indicates the location of the target. An enlargement of the final part of the trial can be seen in the grey square. (b) Evolution of the y coordinate of the participant's position during the trial. (c) Vibration patterns corresponding to the exploration depicted in (a) and (b).

Final position.

A repeated-measures ANOVA was performed with target location (3 levels) as the within-subjects factor and the final position of participants (the y coordinate in Figure 5.7a) as a dependent variable. The ANOVA revealed a significant effect, $F(2,\, 100) = 8779.5$, $p < .001$, $\eta_p^2 = .99$. This demonstrates that the vibrotactile SSD allowed users to distinguish the target locations.

Signed and absolute errors.

Two repeated-measures ANOVAs were performed with target distance (3 levels) as the within-subjects factor, with the signed and absolute errors as dependent variables. As shown in Table 5.2, significant effects were obtained for both dependent variables; performance was most accurate for the farthest target because participants showed less overestimation for that target. The average signed error was 15.9 cm. This means that, on average, participants stopped 15.9 cm after the center of the target. Because the target was circular and had a diameter of 20 cm, this was 5.9 cm beyond the edge of the target. The average magnitude of the error was 19.7 cm (*SD* = 14.7).

Table 5.2: Results of Repeated-Measures ANOVAs with Target Distance (d_1 to d_3) as Within-Subjects Factor for Experiment 2

	d_1 **300 cm**		d_2 **500 cm**		d_3 **700 cm**				
	M	*SD*	*M*	*SD*	*M*	*SD*	*F(2,100)*	*p*	η_p^2
Signed Error(cm)	18.3	18.2	20.3	17.1	9.0	19.1	7.1	.001	.12
Absolute Error (cm)	20.8	15.2	21.6	15.4	16.3	13.2	3.2	.045	.06

Trial duration.

Performing the task required more time than in Experiment 1. Participants used a mean of 19.1 s (*SD* = 13.3) before they decided that they were at the target. Trial duration was not related to accuracy as measured by the magnitude of the error (r[155] = -.12, p = .13).

Movement variables: Number and amplitude of oscillations.

The behavior of overshooting the target and tracking back happened in 66.9% of the trials (*SD* = 47.2). In those trials, at least one oscillation of more than 10 cm was observed (Figure 5.7b). In 20.4% of the trials participants oscillated more than once. The number of oscillations (*M* =1.8, *SD* = 3.4) was not related to the magnitude of the final error (r[155] = -.09, p = .25). The average velocity was 37.3 cm/s (*SD* = 9.0). The distance covered in a straight line was 577.3 cm (*SD* = 168.1), which is higher than the minimum distance needed to perform the task without error (500 cm; the mean of the three distances to the target). As implied by the design, the size of the vibrotactile angle at the end of the trial (γ; Figure 5.2a) closely related to the magnitude of the error ($r[155]$ = -.87, $p < .001$). This angle, together with the intensity of vibration, may hence have been used to reduce the error.

5.6.3 Discussion

Experiment 2 showed that the SSD can be used to successfully complete navigation tasks that involve moving toward and stopping at targets located in front of participants. Participants reduced the distance to the target from the initial 3 to 7 m to an average final 5.9 cm beyond the edge of the target. This proves that participants were able to detect and use the distance information provided by the devise. In 66.9% of the trials, the final position was reached after overshooting the target and tracking back.

The lack of previous studies that quantified the distance error prevents us from making comparisons with other SSDs. Relatedly, however, Loomis, Da Silva, Fujita, and Fukusima (1992) reported average distance errors of 55 cm for individuals who were blindfolded after a period of visual preview and then walked to targets placed at distances that were similar to the present ones (4-12 m). Our results can hence be interpreted as indicating that on-line control when using an SSD is superior to control on the basis of vision that is occluded just before the initiation of the action.

Participants in our experiment had an average walking velocity of 37.3 cm/s. In their first experiment, van Erp et al. (2005) reported an average walking velocity of about 4.3 km/h (119.4 cm/s), which is substantially faster than in our experiment. A possible explanation for this difference could be the following. In the study by van Erp et al., although the orientation to the invisible waypoints was based on the vibrotactile stimulation, other aspects of the control of walking were based on regular vision. Also, given that the waypoints in the study by van Erp et al. had a diameter of 15 m, the accuracy of the control was not as important as in our Experiment 2.

5.7 Experiment 3

Experiments 1 and 2 considered orienting toward and approaching a target as two separate tasks. This experiment addressed a more general task: steering and locomoting toward a goal as described in the first experiment by Fajen and Warren (2003). The information provided by the SSD was a function of the distance between the participant and the target, D_{pt}, the vibrotactile angle of the target, γ, and the body-referenced direction of the target, θ. The main purpose of Experiment 3 was to explore the generality of the oscillations observed in the single-dimensional orientation task in Experiment 1a. We hypothesize that the exploratory oscillations will be observed also in this more general task.

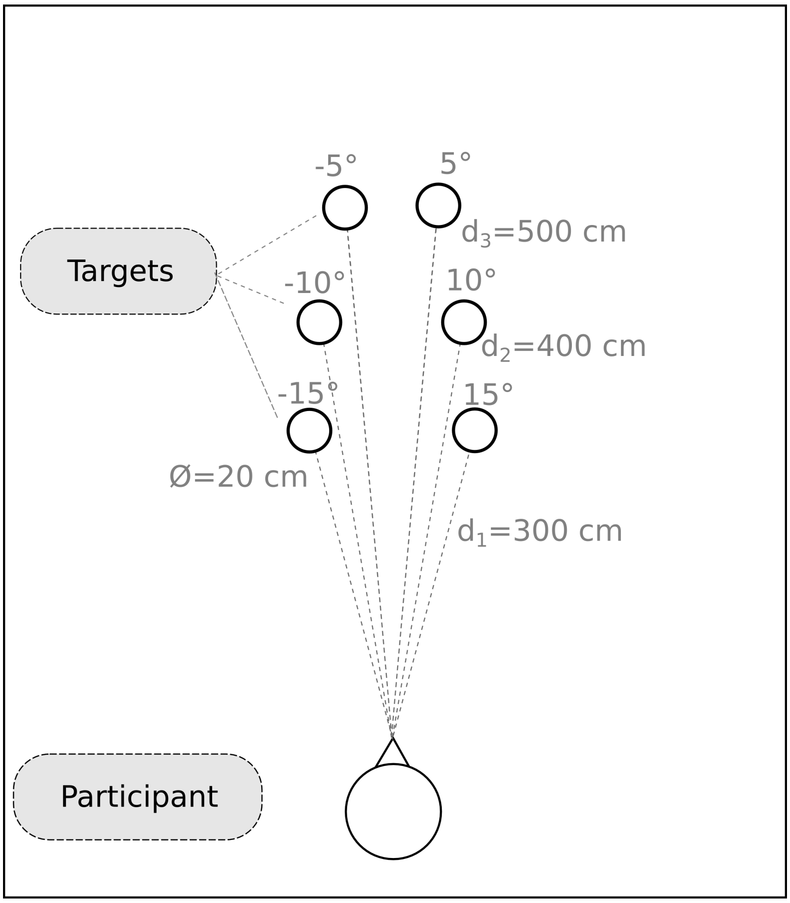


Figure 5.8: Schematic representation of the location of the targets with respect to the participant in Experiment 3. Targets were placed at three distances and six angles, combining Experiments 1 and 2.

5.7.1 Method

Experiment 3 was performed by seven of the participants that also performed Experiments 1a and 2. Four of these participants performed Experiment 3 three weeks after Experiments 1a and 2. The rest of the participants completed the three experiments on the same day, separated by optional short breaks. Participants were asked to walk from a starting position to the virtual target (Figure 5.8).

Similar to Fajen and Warren's (2003) procedure, during the first meter, the SSD did not vibrate. Beyond that point, the SSD provided information about the distance to the virtual target by increasing the intensity of vibration and the number of actuators that were turned on as the distance decreased. The SSD also provided information about the direction of the target in relation to the participant's orientation. Participants could feel the vibration only if the field of sensitivity of the device (60º) was directed toward the target. Participants were asked to navigate toward the target using all the functionalities of the SSD mentioned in the general method. Participants performed three familiarization trials, where targets were located at 30º and 200 cm, 0º and 600 cm, and -30º and 200 cm. After that, they completed 12 test trials: two repetitions of each of the six positions shown in Figure 5.8. The experiment took approximately 30 min.

5.7.2 Results

Overall description of performance.

Participants reported that it was more difficult to reach the target in Experiment 3 than in Experiments 1 and 2. One trial (1.2% of all trials) finished early without the participant finding the target. This trial was not used in the analyses. In four other trials (4.8% of the total number of trials) participants declared that they were unsure of their decisions. Those trials were analyzed along with the rest of the trials. Participants usually moved the upper body turning from one side to the other while they were walking, even during the first meter, which did not include vibration. As in Experiment 1, participants moved the torso with large oscillatory movements at the beginning of a trial and with smaller oscillatory movements later in the trial, as they homed in on the target (Figure 5.9).

Final position.

We examined the effect of target location with repeated-measures ANOVAs. The first two ANOVAs used the x and y coordinates of the participants' final position as dependent variables. As shown in Table 5.3, these ANOVAs revealed significant effects for both coordinates. This demonstrates that the SSD was useful to distinguish the target locations.

Table 5.3: Results of Repeated-Measures ANOVAs with Target Location as Within-Subjects Factor (6 Levels) for Experiment 3

Dependent Variable	*M*	*SD*	*F*	*df* (Factor, Error)	*p*	η_p^2
Final x-Coordinate (cm)	-2.0	62.6	860.7	3.8, 45.0	<.001	.99
Final y-Coordinate (cm)	360.7	91.8	237.9	3.3, 39.3	<.001	.95
Spatial Error (cm)	37.1	21.8	3.9	4.0, 47.7	.009	.24

Two-dimensional spatial error.

The spatial error was defined as the ordinary Euclidian distance between the participant and the target at the end of the trial. This Euclidian distance is depicted by the segment referred to as error in Figure 5.9a. The average spatial error was 37.1 cm ($SD = 21.8$). The repeated-measures ANOVA on the spatial error revealed a significant effect of target location (Table 5.3). This means that the targets were not detected with equal accuracy. Pairwise comparisons with Bonferroni's adjustment for multiple comparisons revealed significant differences ($p = .007$) between the errors for the targets located at -15° and 15° (50.1 vs. 21.4 cm, respectively).

Single-dimensional spatial errors.

When the spatial errors of the coordinates were considered individually, they correlated significantly with the errors as measured by the 2D Euclidian distance between the target and the participants' final position. Nevertheless, the errors in the y direction contributed more to the 2D errors ($r[81] = .99$, $p < .001$) than the errors in the x direction ($r[81] = .25$, $p = .024$).

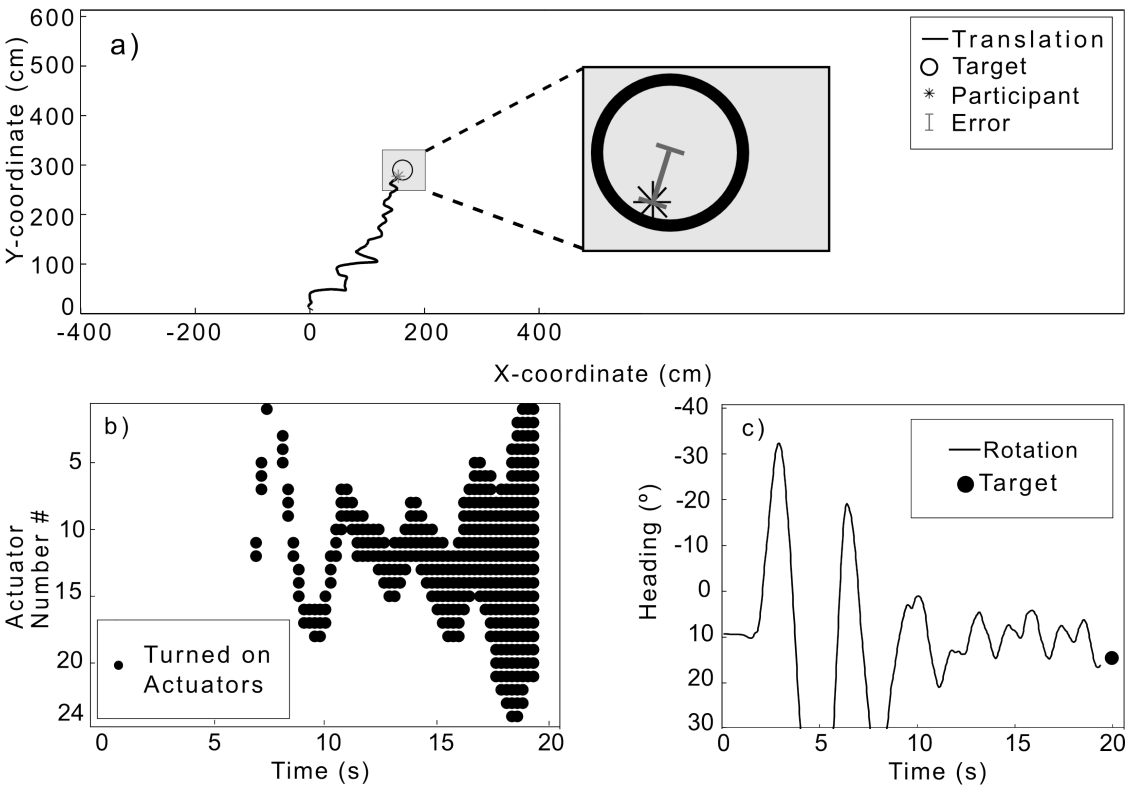


Figure 5.9: Example of a trial from Experiment 3. (a) Evolution of the two-dimensional position of the participant during the trial, with an enlargement of the final part of the trial in the grey square. (b) Vibrational patterns corresponding to the movement depicted in (a). Note that during the first 100 cm the SSD does not vibrate. (c) Evolution of the heading direction during the trial.

Angular deviation and trial duration.

At the moment of the decision, the correlation between the heading direction and the direction of the target was $r[81] = .29$, $p = .008$. The average signed angle D at that moment was 4.5° ($SD = 36.6$). The magnitude of this deviation was 18.9° ($SD = 31.6$). Trials with a smaller final magnitude of the angular deviation also had a smaller spatial error ($r[81] = .42$, $p < .001$). The mean time taken to complete a trial was 29.6 s ($SD = 10.9$). In this experiment, the duration was inversely related to the accuracy of the decision: the longer a trial, the greater the error ($r[81] = .30$, $p = .005$).

Movement variables: Number and amplitude of oscillations.

On average, participants oscillated the body-referenced target angle 16.1 times per trial ($SD = 6.5$; Figure 5.9c). The mean angular range covered in a single trial was 113.6° ($SD = 31.0$). The amplitude of the last half oscillation before the decision was 8.4° ($SD = 8.1$). On average, participants walked at 15.6 cm/s ($SD = 3.0$), which is approximately twice as slow as in Experiment 2. The walking speed was related to the final spatial error ($r[81] = -.39$, $p < .001$). Slower trials were less accurate. Participants covered a mean cumulative angular distance of 580.9° per trial, which is more than six times the angular distance per trial in Experiment 1a (86.7°). On average per trial, the target occupied a vibrotactile angle γ of 25.5° ($SD = 4.5$), participants had 4.9 ($SD = 1.41$) actuators activated in each row (see Figure 5.9b for an example), and the intensity of vibration was at 75.1% ($SD = 11.1$) of the maximum.

5.7.3 Discussion

Participants in this experiment were able to use the SSD to orient and walk toward targets in all but one of the trials. The average final deviation was 37.1 cm, which is 27.1 cm from the edge of the target. We therefore consider performance to be relatively successful. As was the case in Experiment 1a, oscillatory movements were observed. This shows that the oscillations are not a peculiarity of a purely rotational task. The oscillations may have been allowed by the on-line perception-action coupling and they may have facilitated the detection of the direction θ. We believe that having identified and quantified the exploratory oscillatory movements is an experimental contribution that goes beyond the findings of previous studies on SSD based navigation (Cardin et al., 2007; Faugloire & Lejeune, 2014; Jansson, 1983; Tsukada & Yasumura, 2004; van Erp et al., 2005)[6].

5.8 General Discussion

The present article reports a series of experiments involving orientation and navigation using an SSD with an on-line perception-action coupling. The information provided by the SSD was shown to be sufficient to guide users toward invisible targets. In addition to replicating the findings of Faugloire and Lejeune (2014) on orientating, we were able to extend the findings to more complex tasks, and complement them with an analysis of the exploratory movements. Experiments 1a to 1c addressed the ability of users of the SSD to align their body axis with the targets. Experiment 1a used the full functionality of the SSD, leading to average absolute errors of 1.4°. Experiment 1b was performed without on-line perception-action coupling. This led to absolute errors of 12.4°. Experiment 1c was performed with fewer actuators than Experiment 1a (3 instead of 24 columns). This led to absolute errors of 12.3°. Taken together, Experiments 1a to 1c show that accurate performance requires a sufficiently large number of actuators as well as an on-line perception-action coupling. In the experiments with an on-line perception-action coupling (Experiments 1a and 1c), the absolute errors (1.4 and 12.3°, respectively) were smaller than the areas of sensitivity of the actuators (2.50 and 45°, respectively). This is reminiscent of the phenomenon of hyperacuity in regular visual perception. In their study on sensory substitution, Lenay et al. (2003) described cases of hyperacuity as cases with "perceptive resolutions superior to those of the

[6] As a critical note, let us indicate two reasons for the opinion expressed by participants that Experiment 3 was more difficult to perform than Experiments 1a and 2. First, from Figure 5.9b, one may wonder whether the expansion of the vibrotactile stimulation along the approach may have partially masked the information about the direction θ at the end of the trials. Second, the programming error that was present in Experiment 1a (look back to Footnote 4) was present also in Experiment 3. The importance of both of these issues, however, is reduced by the significant correlation between the target direction and the heading of participants at the end of the trial, which indicates that participants' behavior was consistent with the target direction.

material resolution of the matrix of stimulators". As we do, Lenay et al. attributed hyperacuity in sensory substitution to the presence of sensory-motor couplings. Another case of hyperacuity is the one reported by Faugloire and Lejeune (2014). These authors observed absolute errors of about 10° (or more, depending on the experimental condition) while their SSD had areas of sensitivity of 45° per actuator. With absolute errors of 12.4° and areas of sensitivity of 2.5°, hyperacuity was not observed in our Experiment 1b, in which the on-line perception-action coupling of the SSD was suppressed.

The observed pattern of errors and the associated hyperacuity is consistent with our claim that an on-line perception-action coupling is beneficial because it permits the detection of information through exploratory movements. Further evidence for this claim is provided by the following. First, in Experiments 1a and 1c the number of oscillations was higher than in Experiment 1b. Second, the trial duration was longer in Experiments 1a and 1c than in Experiment 1b. Our interpretation of these results is that, in the experiments with an on-line perception-action coupling, participants explored more, and, therefore, needed more time to complete the task, and performed more accurately.

Participants in Experiment 2 walked toward targets placed straight in front of them. Participants stopped, on average, 16 cm after the center of the target, which had a diameter of 20 cm. It is interesting to relate this distance to a particularity of our experiment and the SSD. In this experiment, all actuators of the SSD were activated when participants were at the center of the target. When participants continued beyond the target, the first actuators of the SSD that were turned off were the ones placed the furthest from the body center. These actuators were turned off when participants reached a distance of 15 cm from the center of the target. Hence, the average location where participants stopped was very close to the limit where the first actuators stopped vibrating. Participants who first passed the target and then walked backward were possibly exploring the coupling between the amount of active actuators and their displacement.

In contrast to Experiments 1 and 2, which concerned single dimensions (either turning or walking to the target), Experiment 3 involved two dimensions (turning as well as forward walking). Despite the arguably higher complexity of the task, participants successfully steered and walked toward the target in 98.8% of the trials.

As was the case in Experiment 1a, oscillatory movements around the longitudinal body axis were observed. This demonstrates that the exploratory movements are an important aspect of SSD-based locomotion in general, rather than being a particularity of the single-dimensional orientation task.

The finding that exploratory movements are important is consistent with previous studies about SSDs (Díaz et al., 2012). The finding is also consistent with previous studies concerning perception without SSDs, for example in the areas of regular vision (Bingham & Stassen, 1994) and dynamic touch (Solomon & Turvey, 1988; Turvey, 1996). When perceivers estimate properties of manually held rods, for example, they base their estimates on inertial properties of the rods. To detect the inertial properties, the rods need to be wielded. Moreover, perceivers wield the rods in different ways depending on which of the inertial properties are relevant. This task-specific wielding helps them to selectively perceive either the length or the width of the rods (Arzamarski et al., 2010). Analogous to these finding from dynamic touch, we interpret our findings as showing the advantages of task-specific active exploration. Such exploration allows perceivers to detect and use task-relevant information.

Concerning the information, our SSD provided users with haptic analogues of variables that are known to be relevant for visually guided locomotion (Fajen et al., 2003; Fajen & Warren, 2003). These variables include the egocentric angle of objects and information about distance. The latter type of information was provided through the intensity of the vibration and the vibrotactile angle. The vibrotactile angle followed the same laws of angular size as a function of distance that hold in the case of optics: the closer the object, the larger the angle, and, hence, the larger the number of active actuators. It is well known that expansion-related optic flow variables are highly relevant to the visual guidance of action (Lee & Reddish, 1981; Tresilian, 1999). We find it interesting to speculate that such variables may also be useful in sensory substitution (Cancar et al., 2013). More generally, we believe that it may be fruitful to take into account current knowledge about optic flow variables, and to conceive SSDs that permit access to haptic flow analogues of such variables.

In the introduction, we reviewed three (mutually non-exclusive) reasons concerning the low applicability of SSDs in everyday life. The first reason was the low sensitivity of the skin. Obviously, the sensitivity of the skin is not comparable to the sensitivity of the eyes, and this is relevant to sensory substitution. On the positive side, however, our results indicate that this shortcoming can partially be mitigated by improvements in the contingency of the stimulation with the users' exploration. It is illustrative to reformulate the observed hyperacuity to skin-based measures. Remember that the horizontal distance between the centers of the actuators in our SSD was about 1.7 cm and that the constant and absolute errors that we observed in Experiment 1a were, respectively, 8% and 56% of the angular sensitivity of each actuator. Translated to skin-based measures, these errors can be said to represent 0.14 and 0.95 cm, respectively. The two-point threshold of the skin at the abdomen is about 3 to 4 cm (Weinstein, 1968). Our results therefore indicate that SSDs that allow dynamic user-controlled information detection allow users to achieve levels of performance that go beyond the sensitivity of the skin as measured with the classic two-point threshold.

A second reason that has been suggested for the low applicability of SSDs in everyday life concerns cognitive processing limitations. According to this argument, the central nervous system is not able to process the wealth of information that it may receive if one simultaneously presents information to many actuators and changes the levels of activation at a fast update rate. Consider three counterarguments. First, our Experiment 1a shows that increasing the number of actuators and the refresh rate with respect to previous studies (Faugloire & Lejeune, 2014), reaching values well beyond the detection thresholds, leads to substantial improvements in heading accuracy. Second, according to participants and to the authors' own experience, the use of our SSD is not accompanied by any sign of cognitive overload. Third, in agreement with non-elementaristic approaches (Runeson, 1977, 1994), one may argue that the variables that are detected using SSDs are global sensory flows that dynamically change over time (cf., Meng, Gray, Ho, Ahtamad, and Spence, 2015. If such higher-order variables are what is relied on instead of the set of vibrations of the individual actuators at particular moments, then increasing the number of actuators and the refresh rate should be expected to lead to a more precise detection of these variables, rather than to an increased risk of cognitive overload. In sum, cognitive processing capabilities associated with tactile perception may not be as crucial as previously argued.

This brings us to the third reason for the low applicability of SSDs: the insufficient attention that has been devoted to active exploration and existing knowledge about task-relevant information. Our study shows that this reason may be crucial.

Participants actively explored haptic analogues of information that had previously been shown to be relevant to the visual control of locomotion, and they achieved reasonably accurate performance. This research direction should be further developed in future work. Among other issues, such future research should consider locomotion in more complex task environments, including obstacles and targets instead of only targets. As argued by Fajen and Warren (2003), locomotion as well as route selection in more complex environments can be understood with simple information-action couplings. We believe that these, and other information-action couplings from the literature on the visual control of action, are well suited for implementation using SSDs. Users of such SSDs may find them more useful for everyday-life tasks than the majority of existing devices.

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Chapter 6

Walking Toward Targets: An Experiment With Blind Participants

6.1 Introduction

The most[1] widely-used mobility aid for the blind is the long cane. A main challenge for improving the mobility of visually impaired and blind people is the development of electronic travel aids (ETAs) that improve mobility beyond the mobility allowed by the long cane (Hersh & Johnson, 2008). In this chapter, we argue that the design of ETAs crucially depends on our conception of what mobility is, or, formulated in an ecological way, on our understanding of the informational guidance of movement. An experiment is presented to illustrate this claim.

ETAs consist of three components (Visell, 2009). First, a sensory component that detects certain information from the environment that is not available to the user of the ETA because of the loss of sight. Second, a component that transforms the detected information into the information to be delivered to the

[1] This chapter is accepted for publication with the next reference: Lobo, L., Higueras-Herbada, A, Travieso, D., Jacobs, D. M., Rodger, M., and Craig, C. M. (in press). Sensory Substitution and Walking Toward Targets: An Experiment With Blind Participants. In J. Weast-Knapp and G. Pepping (Eds.) *Studies in Perception and Action XIV*. New York: Taylor & Francis. Psychology Press.

perceiver. And third, a display component through which the novel information is actually delivered. With regard to the display component, the device tested in the present experiment applied vibrotactile stimulation to the abdomen by means of 72 actuators. In the sensory component, the device relied on the distance to the nearest surface in the environment, having a total horizontal field of view of 60º. Finally, the device used a linear function to transform distance into vibration: the closer the object in the direction associated to a particular actuator, the more intense the vibration of that actuator.

The same device has previously been used in a series of experiments by Lobo, Travieso, Jacobs, Rodger, and Craig (2017). The device was designed to allow for active information detection. This aspect of the design was motivated by the ecological view that locomotion trajectories, rather than being planned, emerge dynamically from the on-line coupling of information to action. The ecological focus on information and emergence differs from the focus on spatial representations (Schinazi, Thrash, & Chebat, 2016) and on brain plasticity (Maidenbaum, Abboud, & Amedi, 2014) of other studies concerning sensory substitution. In the reported experiment, blind users of the device walked toward targets. An outstanding non-representational model for the visual control of walking to targets is the one by Fajen and Warren (2003). Their model illustrates how the trajectories followed by participants may emerge from a direct coupling of action parameters to simple optical variables. Our sensory substitution device provided haptic analogues of the optical variables that were important in Fajen and Warren's model: the body-referenced angle of the target and the distance to the target. We hypothesized that our device permits successful performance because it allows the detection of the relevant informational variables.

6.2 Method

Six blind individuals participated. Their mean age was 54.3 years (SD = 10.9). The 72 vibrotactile actuators that were attached to the abdomen were distributed in three horizontal rows of 24 actuators each. The total field of view of 60º was divided in 24 segments of 2.5º associated to the individual actuators. Each actuator vibrated if the target was located in its 2.5º segment of the field of view. The equation used to transform distance in vibration was: $V = V_{max} - 0.12 \times D$, where

V is the voltage level, expressed as a percentage of the maximal voltage level V_{max}, and D is the participant-target distance (in cm). The vibrotactile information was contingent upon the participant's exploration. To achieve this, the participant's position was recorded (at 100 Hz) with a motion capture system (Qualisys AB, Sweden). The detected position and orientation of the participant relative to the target was used to compute the voltage levels. Note that the current device did not include actual distance sensors. A related device, described by Cancar et al. (2013), did actually detect the relevant distances.

Participants were asked to walk to a target. Six target locations were used, which differed with regard to their initial distances and heading directions (3 m and $\pm 15^o$, 4 m and $\pm 10^o$, and 5 m and $\pm 5^o$, respectively). The target was virtual: although the target location determined the vibration, the target was not physically present. Participants verbally indicated when they believed that they had arrived at the target location. Participants completed two repetitions of each of the six experimental trials as well as three familiarization trials (2 m and $\pm 30^o$ and 6 m and 0^o). As mentioned, the intensity of vibration increased when the distance to the target was reduced. In addition, different actuators were active depending on the relative angular location and the angular size of the target. For example, when participants rotated in a clockwise direction, the vibration on the abdomen moved in a counterclockwise (leftward) direction. The vibratory information hence specified target direction and distance.

6.3 Results and Discussion

On 70 of the 72 trials (97.2%), performance was successful in the sense that participants arrived at the location of the target. The two unsuccessful trials (2.8%) and one trial with recording errors (1.4%) were not used in the analysis. An example of a successful trial is shown in Figure 1. Note the oscillatory pattern in the right panel of the figure. This left-to-right oscillation in the vibratory flow occurred because, while participants moved forward, they performed exploratory yaw rotations of the upper body.

The average spatial error (the Euclidean participant-target distance at the end of the trial) was 67.89 cm (SD = 19.87). The mean trial duration was 33.97

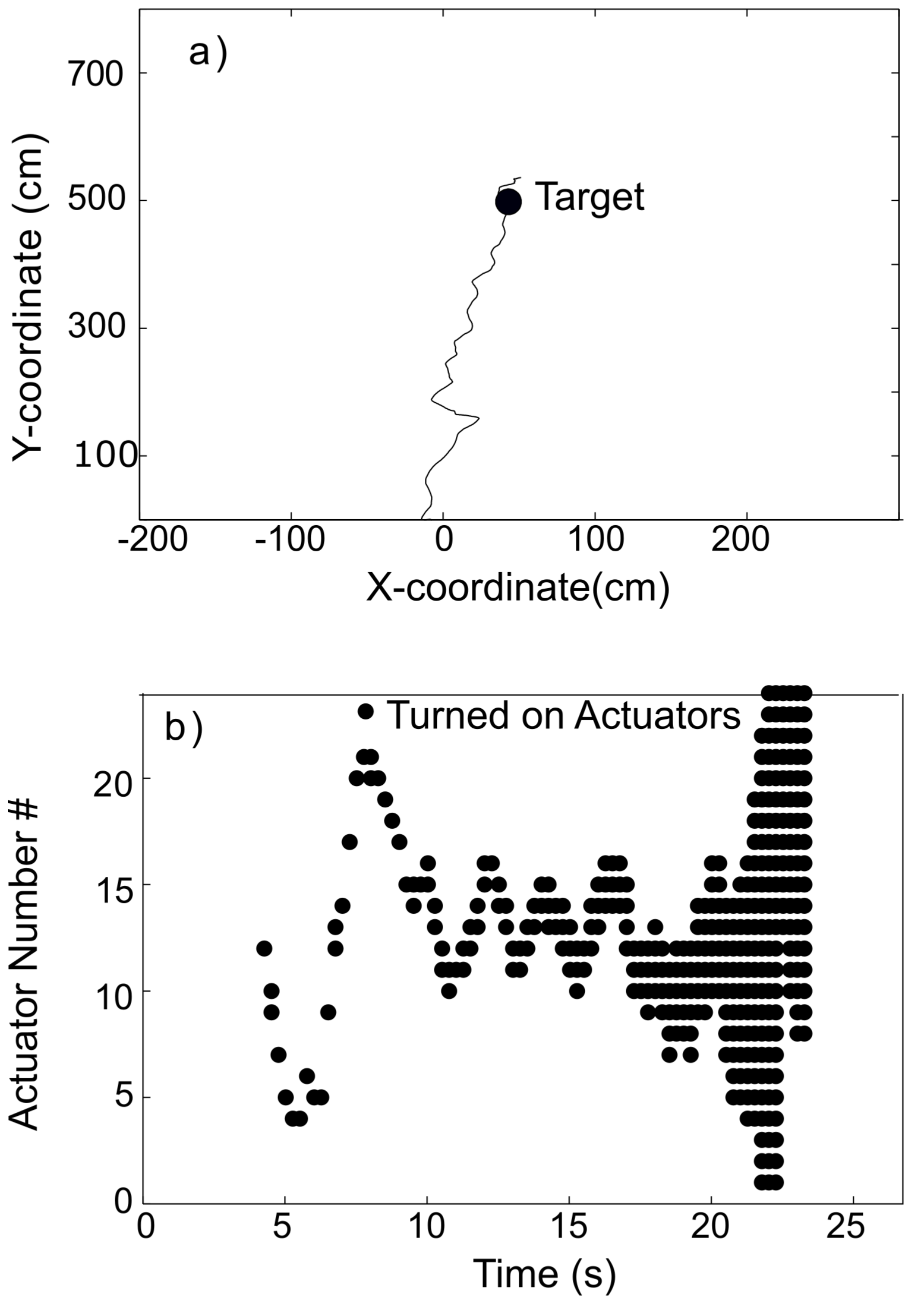

Figure 6.1: One-trial example of the (a) two-dimensional participant position and (b) changing pattern of vibration during the trial. Not shown is the rotation of the upper body.

s (SD =15.20). Participants performed an average of 18.4 (SD = 7.4) oscillatory movements per trial. The mean amplitude of the oscillations was 28.3º (SD = 13.4). The amplitude of the last oscillation before the decision was 7.1º (SD = 3.7). We did not observe a significant effect of the initial target distance on the number of oscillations and neither on the mean amplitude of the oscillations: $F(2{,}66) = 0.03$, $p = .97$, and $F(2{,}66) = 0.08$, $p = .92$, respectively. The trial duration was inversely related to the spatial error: the longer a trial, the larger the error ($r = .40$, $p < .001$). On average, participants walked 18.31 cm/s. This walking speed is substantially lower than the typical walking speed of visually impaired individuals with a long cane (Johnson, Johnson, Blasch, & De l'Aune, 1998).

We compared the performance of the blind participants in the present experiment to the blindfolded sighted participants in a corresponding experiment by Lobo et al. (2017). The blind participants had larger spatial errors (67.89 vs. 39.62 cm; $t[6.5] = 3.2$, $p = .02$). However, this difference is difficult to interpret because the blind participants were older (54.3 vs. 27.6 years, $t[5.9] = 5.6$, $p = .001$) and had a clear disadvantage in terms of general motor abilities. We did not observe differences between the blind and blindfolded participants in other performance-related variables: angular error, trial duration, total distance covered, walking speed, and amount and amplitude of exploratory rotations. Lobo et al. (2017) observed similar exploratory rotations in an orientation task with a fixed participant-target distance.

To summarize, the blind participants in the present experiment successfully reached the target in almost all of the trials. This high level of performance indicates that the tactile sensory substitution device allowed the detection of relevant informational variables—analogues of which are usually detected by the visual system. By coupling these variables to action parameters, the locomotion trajectories may have emerged in an on-line fashion (Fajen & Warren, 2003), without need for trajectory planning on the basis of spatial representations (Schinazi et al., 2016). If this suggestion is correct, then the design of future ETAs should focus on the possibility to actively detect the variables implied in the relevant information-action couplings.

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Chapter 7

Route Selection and Obstacle Avoidance with a Minimalist Sensory Substitution Device

Sensory[1] Substitution Devices (SSDs) and Electronic Travel Aids (ETAs) are designed to assist people navigate under visually impaired circumstances. The design of SSDs and ETAs often relies on the belief that the information supplied by the devices should allow the construction of a spatial mental representation on the basis of which routes are planned. This study, in contrast, illustrates that navigation can be conceived as an on-line dynamic process, without the need of a predefined plan or model of the task. We analyzed route selection with a vibrotactile SSD that informed only about a short spatial range, allowing users at a certain moment and position to perceive only a part of the scene through which the to-be-followed route should take place. Sixty participants performed a navigation task that included a target and five obstacles. The participants were divided in three groups that differed in the used sensory modalities (visual, acoustic and vibrotactile, and visual and vibrotactile). Although participants in the visual condition had better precision in terms of the number of collisions with obstacles and trial duration, no significant differences among the conditions were observed in terms of route selection. We observed a reasonably good adjustment of the selected routes to those

[1]This chapter is based on this manuscript: Lobo, L., Nordbeck, P. C., Raja, V., Chemero, A., Riley, M., Travieso, D., & Jacobs, D. M. (2017). *Route Selection and Obstacle Avoidance with a Minimalist Sensory Substitution Device.* Manuscript in preparation.

predicted by a dynamic model of visually-guided locomotion (Fajen & Warren, 2003), also in the condition based on short-range vibrotactile information. These findings exemplify that route selection may proceed without a mental representation of the full layout and thereby highlights the necessity of building SSDs and ETAs that allow the on-line control of tasks.

7.1 Introduction

Route selection and obstacle avoidance are essential tasks for autonomous navigation. Visually impaired and blind individuals are known to experience problems with their autonomy due to difficulties with avoiding obstacles and walking toward targets. The majority of Sensory Substitution Devices (SSDs) have been designed to cope with the absence of vision, using either touch or hearing as substituting senses. SSDs that are designed to help people navigate autonomously in the absence of vision are typically classified as special-purpose SSDs (Loomis et al., 2012). This is so because, rather than substituting vision as a whole perceptual system, they aim to substitute vision in specific situations—in this case, enhancing mobility in space. Several of these devices, which are also known as Electronic Travel Aids (ETAs), are based on information about the distance to objects measured with lasers, ultrasonic signals, or infrared sensors (Dakopoulos & Bourbakis, 2010; Liu et al., 2010).

In the scientific literature, it is possible to identify two approaches that aim to explain navigation behavior of blind individuals (Thinus-Blanc & Gaunet, 1997). The first approach, known as cumulative model (Schinazi et al., 2016), states that representations are key to navigation behavior and that these representation are visual in nature. According to this approach, congenitally-blind and early-blind individuals should show considerably worse spatial performance than late-blind and blindfolded-sighted individuals. The second approach holds that the relevant spatial representations are amodal. This leads to the expectation that the differences in navigation behavior between individuals with different on-set times of the blindness should be limited, especially when a short adaptation is allowed. This second approach has accumulated more evidence in recent years (Tinti, Adenzato, Tamietto, & Cornoldi, 2006). The evidence partly comes from studies conducted with

SSDs (e.g., Chebat, Schneider, Kupers, & Ptito, 2011; Stronks, Nau, Ibbotson, & Barnes, 2015).

Notwithstanding the debate concerning the on-set of blindness and performance, the visual representation and amodal representation approaches share the belief that navigation behavior is based on internal representations. A third approach, referred to as information-based control approach, holds that representations are not necessary, because navigation is controlled on-line on the basis of information that emerges during the action (Kolarik, Scarfe, Moore, & Pardhan, 2017, p. 18). In terms of the differences between early-blind and late-blind individuals, the predictions of this approach are similar to those of the amodal representation approach. These two approaches differ, however, with regard to the claimed role of route planning. Route planning is indispensable in the amodal representation approach and irrelevant in the information-based control approach. This difference affects the design of SSDs. According to the amodal representation approach, SSDs should provide a sufficiently complete description of the scene to make route planning possible. In contrast, according to the information-based control approach, the user should have access to information that permits on-line control, meaning that the SSD does not need to provide the user with a general description of the layout.

Advancing in the design of special-purpose SSDs for navigation requires one to establish the specific information needed to effectively perform the navigation task. As long as this information is provided to users in a sufficient manner, it seems reasonable to assume that the lesser the complexity of the SSD, the better. For many tasks, however, what the specific information is and how minimalistic an SSDs that presents the information may be are still open questions. In part this is due to a lack of specific studies. As argued by Faugloire and Lejeune (2014), there is a shortage of studies with vibrotactile SSDs on navigation that report quantitative measures of performance other than task duration. Early studies by Jansson (1983), Guarniero (1977), Zelek et al. (2003) were optimistic about the possibilities of tactile SSDs for autonomous navigation, but these studies did not report detailed measures of performance. The lack of such measures makes comparisons of the effectivity of the devices and of the usefulness of the provided information difficult.

Our aim in this study, then, is twofold. First, we aim to illustrate that route selection with a vibrotactile SSD in a real-world environment may occur in an on-line manner, as claimed by the information-based control approach, rather than on the basis of visual or amodal representations. Second, we aim to test whether a particular minimalist SSD —the Enactive Torch, consisting of a single vibrotactile actuator attached to the wrist—is sufficient to provide the information relevant to a complex navigation task. The stimulation provided by the Enactive Torch is contingent on the users' exploratory movements (Favela et al., 2014; Froese et al., 2012), which has been argued to be a key point to follow a unique pathway in a maze (McGann, Froese, Bigge, Spiers, & Seth, 2011).

An important feature of the Enactive Torch, with regard to our first aim at least, is that it provides information about the egocentric distance in a single direction in a relatively short spatial range (between 20 and 150 cm). This means that no direct information is available concerning allocentric distances and that, at a certain moment and from a certain position, only a part of the whole spatial layout can be perceived. For users of the Enactive Torch it is therefore impossible to represent and preplan the full to-be-followed route from the beginning of the task. It follows that the routes of users of the Enactive Torch necessarily emerge during the action. Hence, if route selection with the Enactive Torch matches route selection under visual guidance, this would offer tentative support for the information-based approach to route selection, which, for visually-impaired navigation, is the least explored explanation for route selection.

The most prominent information-based model to study route selection and obstacle avoidance is the one proposed by Fajen and Warren (2003) and Fajen et al. (2003). This model has been used, for example, to study the interception of moving targets (Fajen et al., 2008), robot navigation (Huang, Fajen, Fink, & Warren, 2006), and collective behavior in crowd locomotor dynamics (Bonneaud, Rio, Chevaillier, & Warren, 2012). In the model, obstacles are described as repellers and targets as attractors. The strength of the repellers and attractors depends on their distance. Both are included in the model using the object angle detected by an agent in an egocentric reference framework. The model is consistent with the view that route selection is an emergent behavior that does not need a predefined plan that is first set up and then executed. More formally, Fajen and Warren's (2003) model describes locomotion toward a target with a differential equation that is based on the person's direction of motion, ϕ:

$$\ddot{\phi} = -b\dot{\phi} - k_g(\phi - \psi_g)(e^{-c_1 d_g} + c_2) + \Sigma_{i=1}^{\#obstacles} k_o(\phi - \psi_{o_i})e^{-c_3|\phi - \psi_{o_i}|}(e^{-c_4 d_{o_i}}), \quad (7.1)$$

being $\ddot{\phi}$ the angular acceleration, $\dot{\phi}$ the angular velocity, ψ_g the goal angle, ψ_{o_i} the angle of each obstacle, d_g the goal distance, and d_{o_i} the distance to each obstacle. The remaining terms b, k_g, k_o, c_1, c_2, c_3, and c_4 are parameters that affect variables with regard to damping, stiffness, attraction and repulsion. To the best of our knowledge, despite the relevance of this dynamic model, the model itself has not been applied in sensory substitution, and only one previous sensory-substitution study used the related experimental paradigm (Lobo et al., 2017).

We performed an experiment with a real-world task in which route selection is essential to avoid obstacles and reach the target. The experiment included several conditions in which participants received visual, auditory, and/or vibrotactile information. In the first condition, participants wore vision-reducing goggles simulating a severe loss of vision with similarities to tunnel vision, a symptom common in eye diseases such as glaucoma or retinitis pigmentosa (Robinson et al., 1997; Vargas-Martin & Peli, 2006). In this condition—referred to as V, as abbreviation of visual—no limit in the spatial length of detection was present; participants could detect the target and all obstacles from the start, although with a small visual angle. In the second condition, referred to as S+ET condition, a sound source (S) was placed near the target and blindfolded participants used the Enactive Torch (ET). In this condition the target could be detected from the beginning of the trial, but, due to the limited range of the Enactive Torch, the obstacles could not. The third condition, referred to as V+ET, was an intermediate condition in which participants wore the vision-reducing goggles (V) and used the Enactive Torch (ET).

One may expect that obstacle perception with vision, even if limited in angle, is superior to obstacle perception with the Enactive Torch. Because of this, we hypothesize that better performance will be observed in the V condition than in the S+ET condition in terms of the trial duration and the number of times that obstacles are touched. The fact that the range in which obstacles can be detected in the S+ET condition is shorter than in the V condition means that it is impossible in the S+ET condition to plan the full route to the target in advance. Consistent with the information-based control theory, however, we hypothesize that such route planning is not necessary. As a consequence, we expect the routes followed in the V and in the S+ET conditions to be similar. With regard to third condition, the V+ET condition, we hypothesize that vision will dominate and thus that the results of the V+ET will be more similar to the results of the V condition than to those of the S+ET condition.

7.2 Method

7.2.1 Ethics Statement

The research project was approved by a local Institutional Review Board (IRB). Written informed consent was obtained from all participants.

7.2.2 Participants

Sixty students of the University of Cincinnati (36 women and 24 men,$M_age = 20.6$ years, $SD = 2.8$) participated in the experiment. None of them had used sensory substitution or similar assistive devices before. All participants were right-handed and had normal or corrected-to-normal vision. Participants received course credit in return for their participation.

7.2.3 Apparatus

A schematic representation of the experimental set-up can be seen in Figure 7.1. The exploration area had an extension of 500 × 700 cm. Five rectangular foam obstacles of 90 × 27 × 21 cm (height, width, and depth) were placed in the area in configurations described below. A cylindrical target with a diameter of 9 cm and a height of 210 cm was placed at the center of the farthest edge of the area. An eight-camera motion capture system (Optotrak Certus, Northern Digital Inc., Canada)

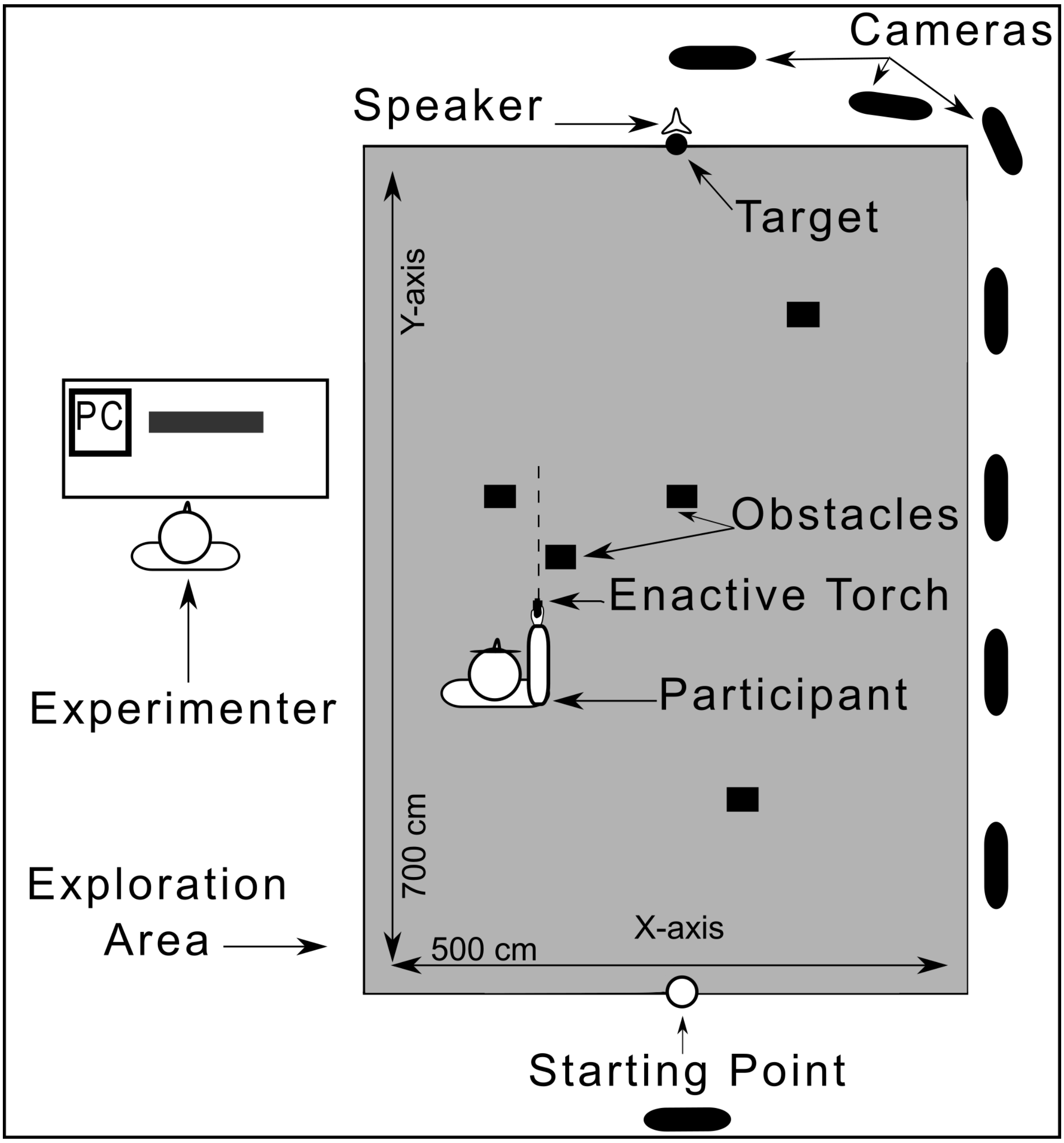

Figure 7.1: Top-view of the experimental set-up.

registered the position of markers located on the top of the head (attached to a cap) and one marker on the right wrist. The position of the markers was registered at 120 Hz.

The vibrotactile device used in the experiment was the Enactive Torch Version 5 (Figure 7.2a; Favela et al., 2014; Froese et al., 2012). This battery-powered device consists of an infrared sensor that works as a rangefinder and a vibrotactile actuator that is attached to the wrist with Velcro band. The infrared sensor covers a range of 20 to 150 cm in a straight line that coincides with the pointing direction. An Arduino pro-mini microcontroller converts the distance to the first-encountered object, as measured by the sensor, into a voltage level that is transmitted to the actuator. The intensity of vibration of the actuator is inversely proportional to the distance measured by the sensor. That is, when the distance to the object increases the intensity of vibration decreases and, conversely, when the distance to the object decreases the intensity of vibration increases. The voltage level delivered to the actuator is 5 V, the maximum, at a distance of 20 cm; and 0 V, the minimum, at a distance of 150 cm.

In the S+ET condition, participants heard a pink noise of 80 dB emitted by a speaker placed just behind the target at a height of 125 cm. In the other two conditions, V and V+ET, participants wore vision-reducing goggles fashioned from welding goggles. The goggles consisted of an opaque surface with a hole of a diameter of 0.2 cm (Figures 7.2b and 7.2c), simulating impaired vision.

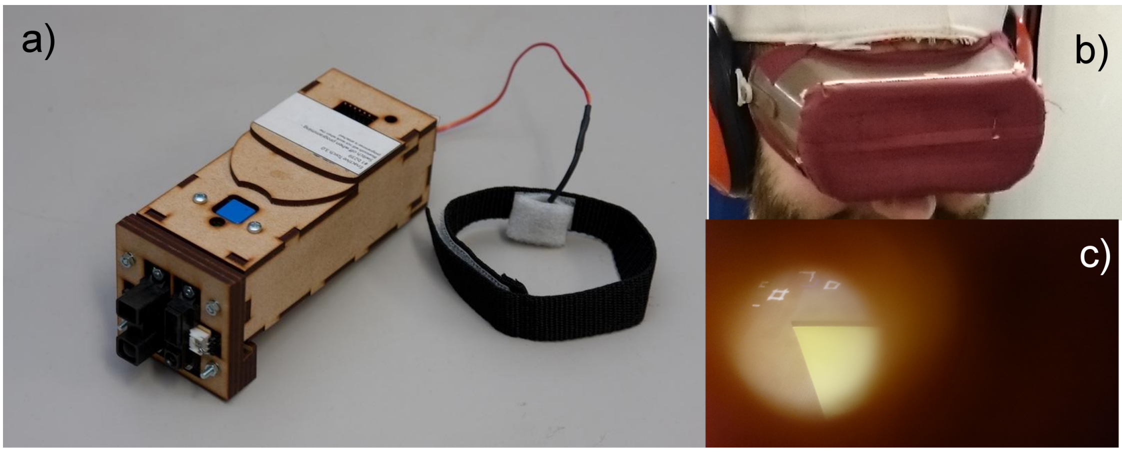

Figure 7.2: (a) Enactive Torch Version 5 (picture retrieved from http://enactivetorch.files.wordpress. com/2008/01/et5.jpg, July 8, 2016). (b) Vision-reducing goggles. (c) Picture taken through the vision-reducing goggles.

7.2.4 Design

The most relevant experimental manipulation concerned the performance condition. Participants in the first condition, the V condition, performed the task with the goggles, but without the Enactive Torch and without any sound. Participants in the second condition, the S+ET condition, performed the experiment while pink noise was played at the target location, blindfolded, and using the Enactive Torch. Participants in the third condition, the V+ET condition, wore the vision-reducing goggles and used the Enactive Torch.

Table 7.1: Coordinates of the Obstacles in the Ten Spatial Configurations

Configuration	**Coordinates (x, y) of the Five Obstacles**									
Number	x_1	y_1	x_2	y_2	x_3	y_3	x_4	y_4	x_5	y_5
1	-0.5	3	1.5	3	-1	3.5	0.5	4	0	5
2	0.5	1.5	-1	3.5	-1.5	4	0	4	-1	5.5
3	0.5	2	0.5	2.5	-1	4	-0.5	4	-1.5	4.5
4	1.5	2	-0.5	2.5	0.5	2.5	-0.5	3.5	-1	5
5	-0.5	2	1.5	3.5	0	3.5	-1	3.5	-0.5	6
6	0.5	3	-1	3	1	4	0	4.5	0	6
7	0	1.5	1	1.5	1.5	5	0	5.5	-0.5	5.5
8	0.5	1.5	1.5	2.5	-1.5	2.5	-0.5	4.5	-1	4.5
9	0	1.5	1	2	-1.5	2	1.5	3.5	0	5.5
10	0.5	2	1	3.5	-0.5	3.5	1.5	4.5	0.5	6

Note. Values are given in m from the starting position (coordinates: $x = 0$, $y = 0$). Simulations following Fajen, Warren, Temizer, and Kaelbling (2003) model were used to discard configurations that led to trivial or impossible trajectories.

In each experimental condition, ten spatial configurations were used. The x and y coordinates of the obstacles in each configuration are shown in Table 7.1. These ten spatial configurations were randomly divided in two series of five configurations. For each participant, only one of the series of five configurations was used. Each participant performed 20 trials: four repetitions of the same series of five spatial configurations. The order of trials was randomized within a series. After the randomization, the twenty trials were performed in ascending or descending order (from Trial 1 to Trial 20 and vice versa). Said more precisely, the 20 participants assigned to each performance condition were subdivided in four subgroups. The first two subgroups used the first series of configurations and an ascending and descending order, respectively; the third and fourth subgroups used the second series of configurations.

7.2.5 Procedure

Prior to the experiment, participants were provided with a brief explanation of the task and the apparatus. They received the following instructions: "You will be placed at one side of the room and you will be asked to walk toward a target several meters away. On your way, you may encounter foam obstacles that you should try to avoid. Your task consists of touching the target with your left hand without touching the obstacles." The experimenter showed them one of the obstacles, the target, and the starting position, mentioning that only the location of the obstacles changed between trials. A brief condition-specific practice was performed before the 20 experimental trials.

Practice in the V condition.

Participants, standing near the target, first turned so as to stand with their back facing the target and put the goggles on. The target was then moved to the left or right and the participants were instructed to turn and visually search for the target. After this single-trial practice, the experimenter accompanied the participants to the starting point, where they waited with their back toward the target.

Practice in the S+ET condition.

. Participants in the S+ET condition were first assessed on their ability to localize the sound. They were placed at two different locations, while blindfolded, and asked to point to the location of the source of the pink noise (i.e., the target location). Participants were given the opportunity to explore the functioning of the

Enactive Torch, pointing to one hand while holding the device with the other hand. The experimenter then placed the target and one obstacle behind the participants and gave them the instruction to turn around and inspect the two objects with the Enactive Torch, reporting the comparative height and width. After that, the participants turned 180 degrees and the target was moved backward. The experimenter placed an obstacle 250 cm from the participant in the direction of the target and 50 cm displaced to the right side. Participants were instructed to turn around 180 degrees and to walk toward the target while scanning on their right side with the Enactive Torch. The practice session ended when participants reported that the obstacle was located straight to their right.

Practice in the V+ET condition.

Participants in this condition first received the same short practice as participants in the V condition. After that, they completed the same practice with the Enactive Torch as participants in the S+ET condition.

Common procedure.

After the condition-specific practice, the experimenter placed the motion-capture markers on the participants' body. Participants moved to the starting position and waited with their back toward the target. The experimental trials started with the experimenter saying "go" in the V and V+ET conditions, and with the onset of the pink noise in the S+ET condition. At the beginning of the trials participants turned around and began walking to the target. A trial finished when participants touched the target with their left hand, after which the experimenter accompanied them back to the starting position. Between trials, the experimenter rearranged the spatial configuration of the obstacles.

7.2.6 Data Processing

Performance errors and movement variables were analyzed. The experimenter manually registered the performance errors, defined as touches of the obstacles. One trial (0.1% of total) was not registered and it was considered missing data in further analyses concerning performance errors. The movement variables were recorded with the motion capture system and participants' trajectories were registered using the head markers. In total, 39 trials (3.3%) had irremediable data recording errors and those trials were discarded in further analyses that involved data recorded with the motion capture system. In the rest of the trials (n = 1161), a mean of 14.21% of frames were not properly registered and those data were interpolated with the function interp1 in Matlab (Mathworks, Inc.). The data were filtered with a forward and backward 4th-order low-pass Butterworth filter with a cutoff frequency of 0.6 Hz. Similarly to the data processing in Fajen and Warren (2003), in order to compare the observed trajectories to the trajectories predicted by the model, we binned each value of the participants' trajectories in the x coordinate (see Figure 7.1 for detail about the axes) in intervals of 10 cm along the y axis. Usually, the observed trajectories ended before the target due to the distance between the top of the head, where the tracking markers were placed, and the extended arm that touched the target. Each trial started with participants' backs facing the target and a subsequent rotation of approximately 180º. For these reasons, when comparing observed and predicted trajectories, we discarded the first and the last meter of the binned data along the y axis. The starting position for each modelled trajectory was the first value from its corresponding observed trajectory.

7.3 Results

7.3.1 Performance Variables

Participants successfully reached the target in 100% of the trials. They completed the task without touching any obstacle (a performance error) in 69.7% of the trials, with one error in 22.0% of the trials, and with two or more errors in 8.3% of trials (Table 7.2). Participants needed, on average, 29.3 s (*SD* = 16.2) to complete the trials.

To compare the performance errors and trial durations among the performance conditions, we averaged out the negligible effects of trial order and spatial configuration. This was done by averaging the measures over subsets of four participants

Table 7.2: Number and Percentage of Performance Errors for Each Performance Condition

	Performance Condition			
Performance Errors	V	S+ET	V+ET	Total
None	326 [81.5%]	245 [61.4%]	265 [66.3%]	69.7 %
One	58 [14.5%]	109 [27.3%]	97 [24.3%]	22.0 %
Two	16 [4.0%]	37 [9.3%]	33 [8.3%]	7.2 %
Three	0 [0.0%]	8 [2.0%]	4 [1.0%]	1.0 %
Four	0 [0.0%]	0 [0.0%]	1 [0.25%]	0.1 %

Note. Percentage data between brackets refer to percentage of performance errors within the performance conditions.

that used different trial orders and different series of spatial configurations. A main advantage of this procedure was that it allowed us to have normally-distributed data. The performance errors were analyzed with a one-way ANOVA, using the factor performance condition with the levels V, S+ET, and V+ET. A significant main effect was observed, $F(2,\ 12) = 6.3$, $p = .013$, $\eta_p^2 = .51$. Subsequent post hoc analyses using Tukey's HSD tests (alpha level = .05) revealed that there were significantly fewer errors in the V condition than in the S+ET condition (Table 7.3).

Table 7.3: Means and SDs for Performance and Movement Variables in each Performance Condition

Performance Condition	**Performance Errors**	**Trial Duration**	$Distance_{OP}$	$Dispersion_{OA}$
V	0.2_a (0.1)	19.4_a (2.6)	36.3_a (29.7)	16.9_a (5.8)
S+ET	0.5_b (0.2)	38.1_b (5.9)	40.9_a (30.1)	23.1_a (5.9)
V+ET	$0.4_{a,b}$ (0.2)	30.9_b (7.8)	38.8_a (27.3)	22.1_b (6.0)
Total	0.4 (0.2)	29.5 (9.6)	38.7 (29.1)	20.7 (6.4)

Note. Each subscript letter denotes a subset of variable performance condition whose observed means do not differ significantly from each other at the .05 level.

A second one-way ANOVA with performance condition as factor was performed with trial duration as dependent variable. There were significant differences among the conditions, $F(2,\ 12)$ =12.9, p = .001, η_p^2 = .68. Tukey's HSD tests revealed significant differences between the V condition and both the V+ET and S+ET conditions (Table 7.3). In the latter conditions, the mean duration per trial was approximately 1.6 and 2 times longer, respectively, than in the V condition.

7.3.2 Movements Variables

The trajectories were studied with regard to the spatial configuration of obstacles and the performance condition (Figure 7.3). For each observed trajectory, we computed the associated predicted trajectory using the dynamic model defined in Equation 7.1. We used the parameter values of simulations #1 and #2 of Fajen et al. (2003): b = 3.25, k_g = 7.5, k_o = 198, c_1 = 0.4, c_2 =.4, c_3 = 6.5, and c_4 = 0.8. The simulations of Fajen et al. assumed a constant velocity of 1 m/s, which we reduced to 0.25 m/s so as to match the above-mentioned trial duration. The distances between observed and predicted trajectories for each binned data point (difference d_i in Figure 7.4) were averaged in each trial. The mean distance between the observed and predicted trajectories ($Distance_{OP}$) for all trajectories was 38.7 cm (SD = 29.1; Table 7.3). We conducted a one-way ANOVA to test the effect of performance condition (V, V+ET, and S+ET) on $Distance_{OP}$. The ANOVA did not reveal a significant effect of performance condition, $F(2,\ 1158) = 2.4$, $p = .09$.

The routes followed by participants were analyzed per spatial configuration of obstacles. When more than four trajectories per spatial configuration and per performance condition coincided in terms of the sides at which the obstacles were passed, a new route was identified (see Figure 7.5 for an example of route identification). In one spatial configuration of obstacles (#8) only one route was identified, in six spatial configurations (#2, #3, #4, #5, #6, #10) two routes were identified, and in three spatial configurations (#1, #7, #9) three routes were identified. In total, 22 routes were identified and 973 trajectories (83.8% of all observed trajectories) followed one of these routes. We studied the corresponding predicted trajectories of these 973 observed trajectories and we found that in 66.0% of trials (n = 642) the route of the predicted trajectory was the same as the route of the observed trajectory. Moreover, in 84.7% of the trials (n = 824) the predicted

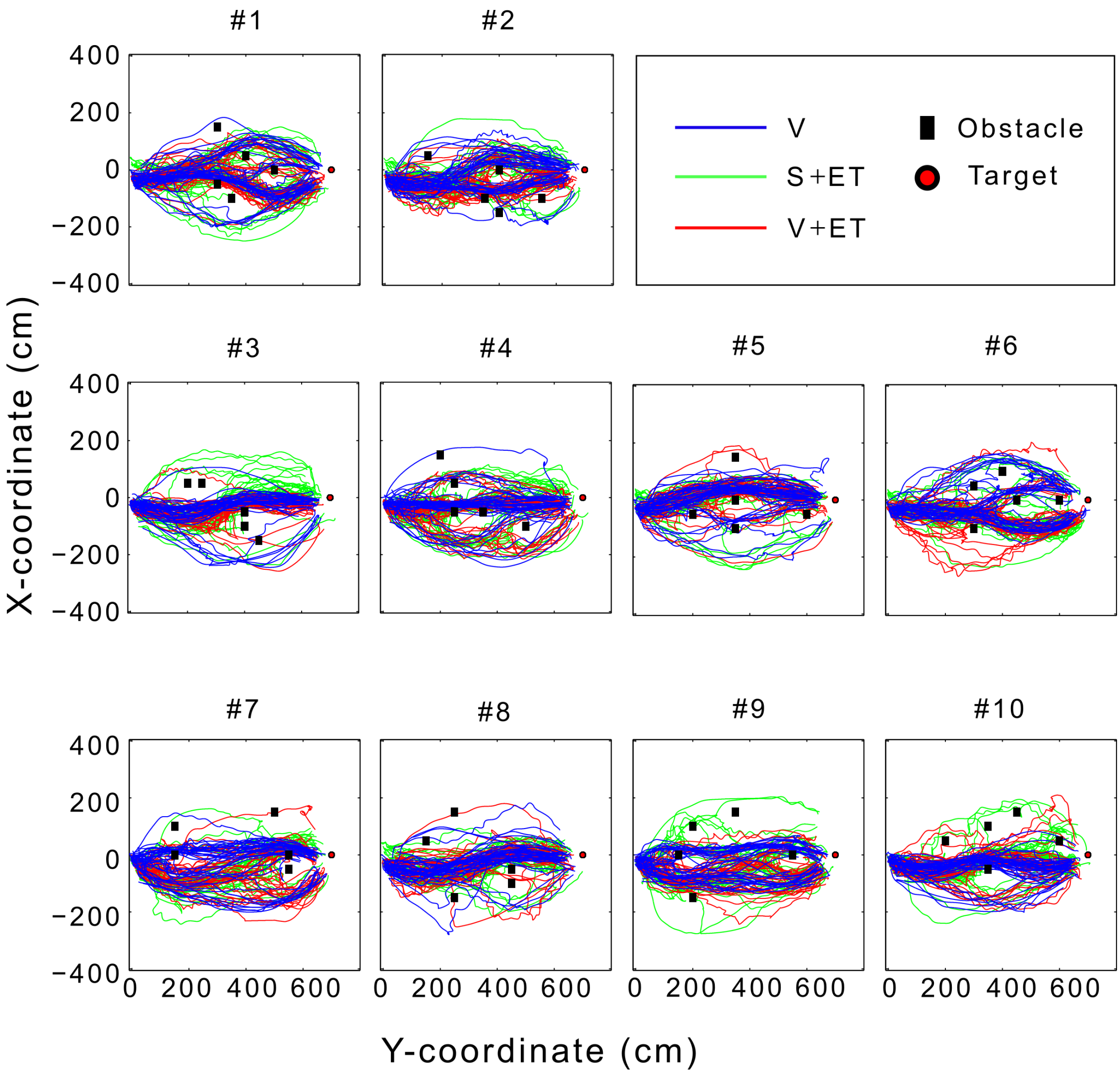

Figure 7.3: Recorded trajectories in the ten spatial configurations of obstacles. The numbers above the plots indicate the specific configuration as shown in Table 7.1. Each subplot includes 10 Participants × 3 Conditions × 4 Repetitions = 120 trajectories.

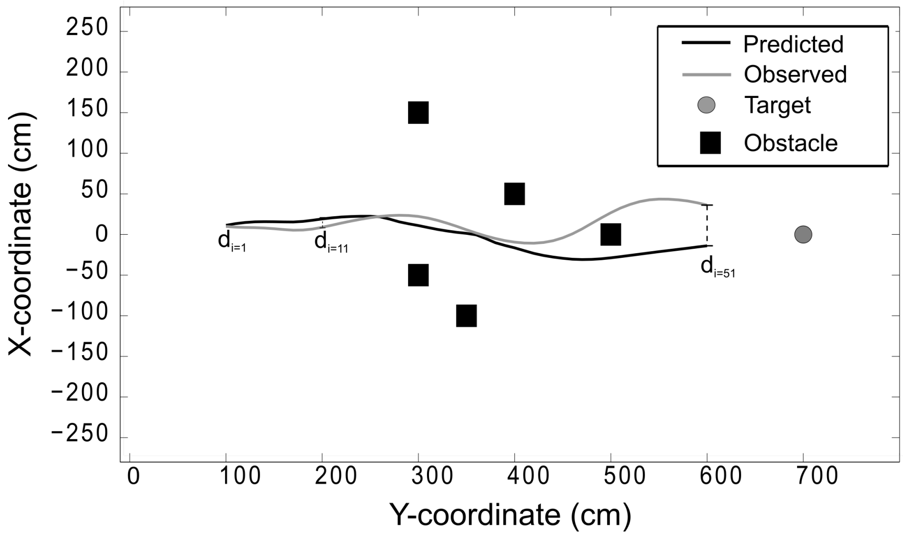

Figure 7.4: Predicted and observed trajectories for one trial. The distance between the observed and predicted trajectories in the x direction is the average absolute value of di calculated every 10 cm along y axis; in this example 22.0 cm. The predicted trajectory was computed from the first x coordinate of the observed trajectory, implying that $d_{i=1} = 0$.

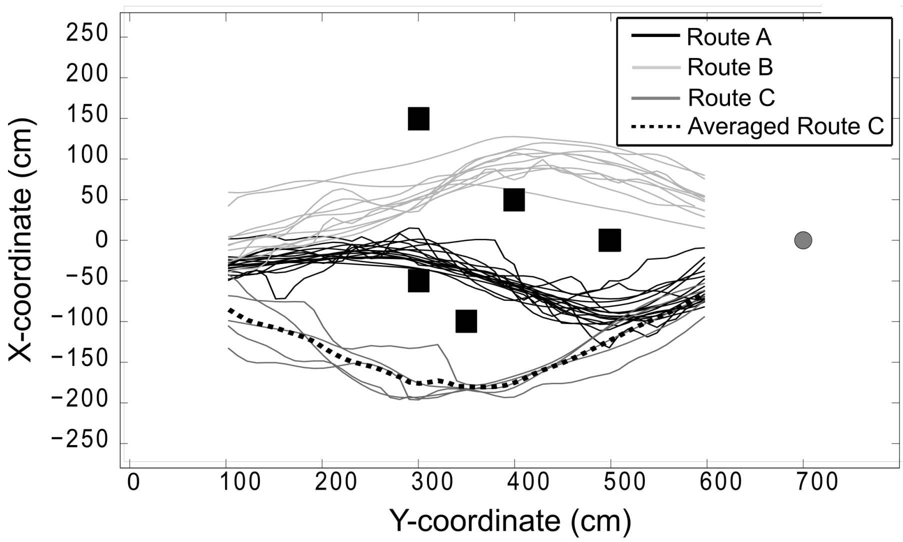

Figure 7.5: Illustration of the three routes (A, B, and C) that were identified with the 10 Participants × 4 Repetitions = 40 trajectories for the V condition and for spatial configuration # 1. The dotted line represent the average of all trajectories included in one route.

trajectory was included in one of the observed routes. There was a high similitude of the routes chosen in each performance condition: the V+ET condition shared 81.0% of the identified routes with both the S+ET and the V conditions while the V condition shared 81.8% of the routes with the S+ET condition, as can be noted in Figure 7.6 where all grouped trajectories in a route were averaged in each performance condition.

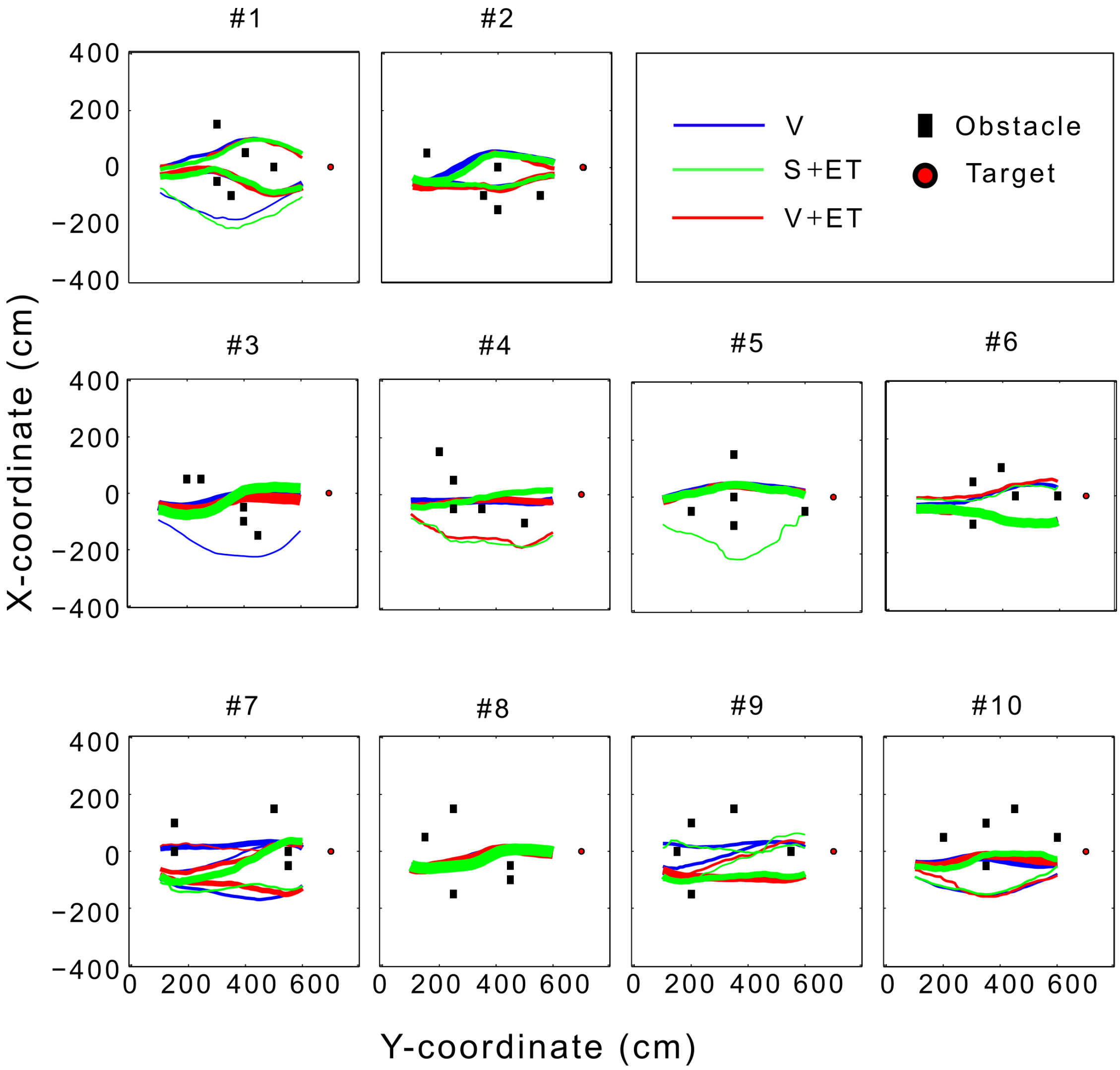

Figure 7.6: Average trajectories for each identified route per spatial configuration and per performance condition. The width of the colored lines is a function of the number of trajectories that are included in the route. For example, in spatial configuration #1, the thin blue line is the average of 5 trajectories (the minimum number of trajectories to produce a route); in spatial configuration #8, the thick green line is the average of 36 trajectories.

The absolute distance between each trajectory and its corresponding averaged route was calculated as a measure of the dispersion of the trajectories ($Dispersion_{OA}$). On average, the $Dispersion_{OA}$ within a route was 20.7 cm ($SD = 6.4$). This dispersion was analyzed with a one-way ANOVA with performance condition (V, V+ET, S+ET) as between-subjects factor. There was a significant effect of this factor, $F(2, 55) = 6.4$, $p = .003$, $\eta_p^2 = .19$. Tukey HSD tests revealed two significant differences between performance conditions (Table 7.3): The V condition had a lower dispersion than the V+ET and S+ET conditions.

7.4 Discussion

Participants in the S+ET condition had a sound source near the target and relied on the Enactive Torch to avoid obstacles. All trials in this condition finished with the participants touching the target, none of the trials were dismissed due to participants feeling lost in the exploration area or unable to avoid the obstacles, and 61.4% of the trials did not show any performance error (i.e., touches of obstacles). These findings are consistent with the theory that route selection does not imply planning the full route in advance on the basis of visual or amodal spatial representations, because participants in this condition had access only to nearby obstacles and hence could not plan the full route in advance.

Participants in the V condition relied only on reduced vision. We did not observe significant differences between the V and S+ET conditions with respect to the distance between the observed trajectories and the trajectories predicted by a model with parameter values of a visually-guided task. Moreover, there was a coincidence of 81.8% with respect to the routes that were followed in more than four trials in the V and S+ET conditions. Our analyses hence did not reveal substantial differences between the routes followed by the Enactive Torch users and those followed by participants with reduced vision. This further supports the theory that routes are controlled on-line rather than being planned in advance on the basis of spatial representations.

Although the selected routes were not found to differ substantially, participants in the V condition showed better performance than participants in the S+ET condition in terms of performance errors and trial durations. This seems to indicate that the obstacles were detected with more precision with the reduced vision goggles than with the Enactive Torch. Additional evidence for this claim is provided by the finding that the five or more trajectories included in the identified routes showed a larger dispersion around the average trajectories in the S+ET condition than in the V condition.

Participants in the V+ET condition could use reduced vision as well as the Enactive Torch. Their results were more similar to the S+ET condition than to the V condition. Specifically, they showed worse performance than participants in the V condition in terms of the performance errors, trial durations, and the dispersion of their trajectories around the identified means. This may seem surprising because participants in the V+ET condition could have equaled the V condition in all regards by ignoring the Enactive Torch. We are tempted to give this unexpected finding a positive interpretation: It shows that the Enactive Torch, rather than being perceived as annoying and to be avoided, attracted the attention of participants, who explored and used the device in spite of the availability of reduced vision. A brief comparison of our results with results of previous studies suggests that the Enactive Torch helps users to avoid obstacles equally well or even better than other SSDs. To give a few examples of such previous studies, Maidenbaum, Hanassy, et al. (2014) reported that participants collided once per trial during the last trial of a task performed inside a corridor, Kolarik et al. (2017) reported 93% successful trials in a task in which participants had to detect and circumvent one obstacle, and Chebat, Schneider, Kupers, and Ptito (2011) reported a percentage of correct responses slightly below 60% for blindfolded sighted individuals that used an electro-tactile device for the tongue to avoid obstacles.

To conclude we should mention that there are reasons that prevent us from being too optimistic regarding minimalist devices. For example, rather than with the Enactive Torch, participants in the S+ET condition detected the target auditorily, at least at the beginning of the trials. Similar results can be found in the experiment of Chebat, Maidenbaum, and Amedi (2015), which was performed in a maze using a minimalist device that provided sound and vibration when a surface was detected. Participants avoided obstacles and found the exit of the maze, but there were no targets in the maze. Additional research is needed to indicate how minimalist devices can optimally inform about targets and obstacles at the same time. In addition, although the studied navigation task can be performed with a minimalist device, our experiment does not rule out possible benefits of a larger number of sensors and actuators and of a longer spatial range of detection. Previous studies have shown that a higher number of sensors and actuators enhances the acuity of SSD-based perception (Lobo et al., 2017). In the present task, a higher number of sensors and actuators may be hypothesized to lead to less performance errors and less dispersion of the observed trajectories.

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Chapter 8

General Discussion and Conclusions

8.1 Main Results

This dissertation focused on the usefulness of the ecological approach to the field of sensory substitution. In this section, I will discuss the main results obtained from the five studies described in Chapters 3 to 7.

In Chapter 3, the aim was to know, first, if a haptic SSD placed on the lower leg would be useful to detect and step on ground-level obstacles. Results of the experiment showed that participants were able to perform the task. In addition, several participants had very successful performance, not only regarding the distance to the obstacle, but also regarding its height. The second aim of this study was to investigate the role of practice and training with a SSD. Results indicated that participants improved their performance from the pretest phase to the posttest phase. Interestingly, the range of the lower leg's tilt when participants were about to step on the object increased with practice, which may be attributed to an increase in exploratory behavior due to the design of the SSD. Finally, regarding the third aim, results revealed significant improvements for the group that trained without vision. When participants trained without vision, the range of the tilt just before stepping increased significantly more than the range for those participants who trained with vision.

In Chapter 4, the main goal was to test if SSDs allow the perception of affordances. The rationale was that reliable substitution must allow users to perceive relevant properties of the organism-environment system. The perception of affordances with a SSD would demonstrate a correct functioning of the device. Results of this experiment showed that participants indeed perceived the affordance of climbability. The differences in proportion of steps judged as climbable between groups of tall and short participants disappeared when the data were rescaled using the ratio of step height over the participant's leg length. The maximum height that a participant could climb with regard to her leg (i.e., the critical π-number) was not found to differ from the critical π-number reported in a study in which the same task was performed using regular vision (Warren, 1984). The only difference with the previous findings on visual climbability judgments (Warren, 1984) concerned the limits of the response curve, which did not reach 0 and 100% in our case. This is related to a lower accuracy achieved by SSD users, compared to participants who use regular vision.

As mentioned in Chapter 1, the rationale behind this chapter is comparing the perception of affordances in two perceptual modalities when, to date, only in one of them there are doubts about distal attribution. There has been a great deal of discussion on whether users perceive objects and events as being 'out there', or whether they are just conscious of skin stimulation, being unable of distal attribution when using a SSD. In the reported experiment, there were no explicit questions for participants about distal attribution. Instead, the same experiment that was previously performed in visual perception was performed with a SSD. When a person judges a step as climbable, hardly ever there is a suspicion of her as being conscious merely of her retinal stimulation. The user perceives the step as being 'out there': She handles the object as an object of the world and she judges it as climbable or not. The same reasoning guides the perception of affordances with a SSD: If the user perceives the affordance, we should not doubt her distal attribution.

In Chapter 5, I presented a sophisticated version of previous devices that enhanced the translation of optic information into haptic information. This study aimed to know how users detect information that is specific to environmental properties. It is expected that this knowledge might be useful to extend the use of SSDs and ETAs in everyday life. In this chapter, five experiments were conducted with three tasks: orienting, approaching, and steering toward a target. Participants were able to solve all tasks with successful performance.

Concerning the orientation task, participants in Experiment 1a had an average absolute error of 1.4° with areas of sensitivity of the actuators of 2.5°. In Experiment 1b they had an average absolute error of 12.4° with the same areas of sensitivity of the actuators, but without on-line perception-action coupling. Finally, in Experiment 1c, participants had an absolute error of 12.3° (similar to Experiment 1b) with an on-line perception coupling but with areas of sensitivity of the actuators of 45°, 18 times higher than the ones in Experiment 1b. Oscillations documented in these experiments show the effectivity of exploratory movement to detect useful information whenever a sensorimotor coupling can be established.

Regarding Experiment 2, on average, participants stopped 5.9 cm beyond the edge of the target, which is very close to the moment at which the furthest actuators from the body center were turned off. In two-thirds of the trials overshooting the target and going back was observed. This can be interpreted as the result of participants testing the sensorimotor couplings. Comparing the results of this experiment to those reported by Loomis et al. (1992), Loomis, Da Silva, Fujita, and Fukusima (1992), on-line control with this SSD is better than a control based on first seeing a setup and then perform the task without vision. With haptic on-line control, participants had a reduction of 71% in the absolute error.

In Experiment 3, participants steered toward a target in a combination of Tasks 1 and 2. All functionalities of the SSD worked during this task. The vibrotactile SSD allowed for the detection of the information used in visually guided locomotion (Fajen & Warren, 2003). The body-referenced direction of the target, θ, was indicated using the location of the vibration on the abdomen, and the distance between participant and target was indicated using the intensity and size of the active actuators, therefore allowing the detection of 'haptic expansions' and giving access to τ-like variables. In 98.8% of the trials participants reached the target successfully. They had an average absolute error of 37.1 cm, which indicates a final location 27.1 cm from the edge of the target. Exploratory oscillations were also observed in this task.

In Chapter 6 we saw an example of steering toward a target with visually-impaired people. The aim of this chapter was to test the previous SSD with blind users. Remember that participants in Chapter 5 were blindfolded participants who had regular vision, so, for them, the expansion of an object was the natural way to detect the approach of the object. Testing this device with blind people is extremely interesting, as they do not normally rely on expansions. Results of this experiment showed that in 97.2% of trials participants reached the target and that they had an average absolute error of 67.9 cm, which is 57.9 cm beyond the edge of the target. Although this is a significant difference with respect to the absolute error of the blindfolded participants in the previous chapter, I do not interpret this as a consequence of the on-set times of the visual deprivation. Participants in this experiment were older than participants of Chapter 5, what may have resulted in more mobility problems. In my opinion, it is important to highlight that visually-impaired participants could use vibrotactile information to detect and reach a target of 10 cm (i.e., an object with an area 314 cm^2) in an exploration area of 500 $\times$ 700 cm (i.e., an area of 350000 cm^2, more than 1000 times larger than the target) in approximately 34 s.

Two goals were pursued in Chapter 7. The first aim was to determine whether it is possible to solve a complex navigation task, with a target and multiple obstacles, using a minimalist SSD. The second aim was to illustrate that navigation with a SSD can be explained without appealing to mental representations. The minimalist SSD used was the Enactive Torch, a hand-held pointing device with a single actuator that vibrates as a function of distance. Considering the first aim, it was shown that the Enactive Torch is useful to avoid obstacles. Even so, in my opinion (and against the intuitive idea of minimalist devices) the accuracy of performance would benefit from a larger number of actuators, as well as from a longer spatial range of detection (the range of detection is discussed in Nordbeck & Raja, 2015).

Considering the second aim, three models for explaining navigation with SSDs were presented. Two of these models claim that navigation requires planning the full route in advance on the basis of spatial representations. The spatial representations would be amodal according to one of the models and visual according to the other. A third approach is the one offered by the information-based control approach. Planning is irrelevant in this third approach. The use of a short-range haptic device provided a test of this alternative model (the information-based control approach), which does require mental representations. A main feature of the

Enactive Torch is that it does not provide the user with a general view of the layout, but with egocentric information about obstacles at a distance of at most 1.5 m. Users of the Enactive Torch can hence not construct a full mental representation of the task environment before they engage in the action. It was shown that participants using the minimalist SSD completed the task, and that there were no significant differences in route selection between participants using the SSD and participants using (reduced) vision. Thus, the information-based control approach can be used to explain navigation with a minimalist SSD as well as visually guided locomotion.

8.2 The Ecological Approach to Sensory Substitution: A Challenge to the Cognitivist Approach

From a global point of view, the results of the previous experiments challenge the cognitivist approach. In this section, I will discuss five topics in which the ecological and cognitivist approaches differ. These topics are the role of mental representations, the effect of learning, the relevance of skin sensitivity, the importance of the specificity of information, and the contribution of active exploration.

8.2.1 The Role of Mental Representations

In Chapters 3 and 7, I presented two experiments that affect the debate about mental representations. It has been argued that visual representations are needed to have a correct space perception and, as a consequence, that congenitally blind people cannot perform at the same level as late-blind people. One example is the work of Rieser, Hill, Talor, and Bradfield (1992).These authors argued that individuals with a history of normal vision and a later onset of a visual impairment are more sensitive to nonvisual information about spatial structure than congenitally or early-blind individuals. Subsequent reviews, such as the ones of Schinazi et al. (2016) and Thinus-Blanc and Gaunet (1997), downplay the impact of the results obtained by Rieser et al. (1992) compared to a majority of studies that argued almost the opposite.

In Chapter 3, the benefits of training without vision can be discussed from the point of view of visual representations. Remember that participants in this experiment had no prior experience with SSDs and that they had normal vision, which implies that they always detected and climbed steps using vision. This experiment showed that participants who trained with vision had worse performance detecting the step than participants who trained without vision. It could be argued that participants in the condition with vision associated visual stimulation with vibrotactile stimulation while performing the task in the training sessions. Then, during the posttest phase, they only had to use the vibrotactile stimulation to visually represent the task. But, if the visual representations would have had a role in this task, we should have seen an improvement in performance for those individuals who could relate vision to vibrotactile stimulation. On the contrary, we observed that the exploration for detecting relevant variables with the haptic device is not optimal when the task was previously solved using vision. Such results question the hypothesis that visual representations are necessary to establish a parallelism in sensory substitution. In contrast, it seems that vision prevents users to rely, at least in part, on vibrotactile information.

Due to the experimental conditions, the extent of the discussion about mental representations in Chapter 3 concerns only the role of visual representations. However, in Chapter 7, I presented an experiment that goes beyond visual representations and discusses the issue of mental representations in general. We found that the use of mental representations, even if we consider amodal representations, is unlikely in route selection. In this study, the experimental conditions of the group of SSD users prevented them to plan a full route in advance. Given that the results from this group did not differ from the groups that theoretically could plan a route, the need for amodal space representations was dismissed. Does it prove that mental representations are not used for route selection? As argued in Chapter 4, claims about direct perception with SSDs always remain open to criticism of skeptics. However, postulating mental representations is not the most parsimonious explanation; Chapter 7, in contrast, offers a more parsimonious one.

From the experimental point of view, methodological decisions are not neutral with regard to the adopted theoretical approach. The experiments presented in this dissertation proposed relevant tasks for agents, in contrast to what has been relatively common in the literature; that is, to design tasks that consider participants as passive subjects whose cognitive processes are based on representations. The problem of considering participants as passive subjects computing representations is part of the vicious circle of the computer metaphor. In my opinion, this vicious circle goes as follows: We tend to use this metaphor to explain that the human mind works as a computer; then, we tend to build technology for people—let's imagine, for example, a SSD—based on the explanations of how the mind works according to the above-mentioned metaphor; and, finally, we test people using the technology that we built as if we were testing a computer. Ecological psychology reacts against the idea of participants as passive subjects and rejects the computer metaphor. Instead, this approach proposes that cognition is explained appealing to the engagement of active organisms with their environments.

8.2.2 The Effect of Learning

Considering errors, results of Chapter 3 revealed that participants in the no-vision condition learned how to use the device better than participants in the vision condition. In this chapter, we also saw that both groups of training equally reduced the trial duration. It is noticeable that the reduction in trial duration happened despite the fact that the no-vision group significantly increased the range of tilt before the step. Therefore, from the perspective of the learning process, the improvement in performance is related to an intensification of exploratory movements in a very specific sense. A possible interpretation of this result is that learning does not necessarily entail a reduction in the exploration, but an optimization of that exploration. In the literature of sensory substitution, it has been common to use trial duration as a measure of learning at the expense of other quantitative measures (Faugloire & Lejeune, 2014). From the data presented here, it can be argued that the sensorimotor coupling contains information that is key to improvements in performance, which means that movement variables and not only performance variables should be studied.

My interpretation is that training programs should be based on the theory of direct learning (Jacobs & Michaels, 2007; cf. Smeeton, Huys, & Jacobs, 2013). With that framework, we might design programs in which the usefulness of variables to perceive a property is manipulated. We could speed up the learning process from novices to experts with programs that can be adapted to each user. As described in Chapter 2, invariants known to be used are needed to present the manifold and the movement of a user in the manifold. Future research could possibly be aimed at the study of the perceptual invariants that are important in sensory substitution and their use in the design of training programs.

8.2.3 The Relevance of Skin Sensitivity

The skin sensitivity has been a major topic in the literature of sensory substitution. For example, the development of the TDU (Chapter 2) after the TVSS was based on the idea that receptor surfaces must be very sensitive to be useful for sensory substitution (Bach-y-Rita et al., 2003). Although the debate about the sensitivity of the different areas in touch with SSDs was not directly studied in this dissertation, it is noticeable that participants considered the devices useful even though they were worn on their lower leg, chest, and abdomen. From a cognitivist view, the tongue would be a better place than the leg to place a haptic device (see, for example, the reflection of spatial sensitivity in Spence, 2014). However, the importance of the sensitivity could be overestimated with respect to the importance of on-line couplings. In this dissertation, the use of the leg, abdomen, chest, and hand allowed exploration with the same area that was in contact with the novel stimulation, so that users could easily exploit the new sensorimotor couplings.

Results from Chapters 5 and 6 (and tests performed by Cancar, Díaz, Barrientos, Travieso, & Jacobs, 2013) suggest that participants might use haptic expansions to detect the approach of an obstacle and its time to contact. In order to use expansions, we need to increase the number of actuators. Due to this increment and the standard size of the actuators reported in this dissertation, the use of a skin area larger than those usually proposed (hands, cheeks, forehead, and hallux; see Kandel, Schwartz, & Jessell, 2000, for a comparison with other areas) was almost unavoidable. In contrast to the change made by Bach-y-Rita and colleagues discarding the TVSS in favor of the TDU (or Brainport) because of its sensitivity (see Bach-y-Rita & Kercel, 2003), my proposal is to increase the amount of actuators even if it means to diminish the importance of skin sensitivity. Doing that, we could have an array in which higher order variables can be detected.

In addition to the importance of exploring with the same area that is in contact with the SSD and the necessity of larger areas for a high number of actuators that

I commented in the previous paragraphs, another reason that reduces the relevance of the skin sensitivity can be posited: usual measurements are made in a passive way. The first reason for the low applicability of SSDs that was considered in Chapter 5 was precisely the low sensitivity of the skin. However, participants in Experiment 1a of that chapter could feel vibration with a difference below 1 cm on the abdomen when the task was performed in an active mode. This seems to indicate a reduction of at least 66% with regard to the two-point threshold reported by Weinstein (1968). This two-point threshold, which has classically been used in studies about sensory substitution, could be less relevant than has been stated by Giudice, Loomis, Klatzky, and Bennett (2014) or Kercel and Bach-y-Rita (2006), for example.

8.2.4 The Importance of the Specificity of Information

In section 2.2.4 I already discussed the importance of identifying which are the specific variables to perform a task in relation to the learning process. A complementary approach to information is described in Chapter 5. In this set of experiments, the SSD provided haptic analogues of variables that are relevant for visually guided locomotion (Fajen & Warren, 2003). The most important of these variables is the body-referenced direction to the target, which was detected trough the location of the vibration in the SSD. The importance of perceptual invariants is key in the explanation of perception by ecological psychology, because the perception of affordances is the result of the detection of information (see the quotation of Richardson's et al., 2008, in Chapter 2). An ecological psychologist, then, typically aims to answer the questions of what the information is that specifies an affordance and whether that information is indeed detected.

The study described in Chapter 4 is a good example of how the detection of relevant information leads to the perception of an affordance. Another example can be found in Chapter 2. In section 2.2.3, I used the term 'dynamic touch' to introduce an experimental paradigm that relates the moment of inertia of a rod (or the inertia tensor when the rod is wielded in three dimensions) to the perceived length as an example of specific information. Another well-known example of specific information, more related to navigation, is the variable τ, which is the angular size of an object in our visual field divided by its own change. This variable has been reported as useful in many experiments after the original description of the variable in the study of the behavior of gannets by Lee and Reddish (1981). The variable τ is specific to the time-to-contact under some circumstances. A related reasoning led to the design of the device used in Chapters 5 and 6. I think that the followed approach guarantees the relevance of the considered haptic flow variables, because these variables are relatively direct 'translations' of optic flow variables that are known to be relevant to visually guided locomotion.

However, the description of what is relevant for a user is not exempt of controversy. Attending to some of the experiments that test the functioning of new devices, it seems that reporting the possibilities for action with a SSD is less relevant than reporting the perception of other, more elementary variables. This issue can be illustrated with the study of Maidenbaum, Hanassy, et al. (2014). In this research, three experiments were conducted, although I only focus on the first one. In that experiment, experimenters asked participants to verbally report the distance of a sheet of cardboard placed in front of the participants while using a hand-held vibrotactile and auditory SSD. The authors reported that one of the three blind participants of their study had great difficulties understanding the "concept of distance in meters" after five minutes of training. The training consisted of an experimenter holding the cardboard to give participants "a feel of the different outputs (for example, 'The board is now 2 meters away, this is what an object at this distance feels like')"(Maidenbaum, Hanassy, et al., 2014, p. 816). This happened even when using the same cardboard location in the test trials and the training trials. In this situation, it seems that a proper evaluation of both blind and blindfolded sighted individuals should rely on the perception of affordances rather than on the distance to objects in meters.

Notice that I used the same word, relevant, to explain the approach of Chapters 4 and 5 at the beginning of this subsection. In the ecological framework, this word has a very specific sense: Something is relevant when it is meaningful for the activities and interests of the organism (Runeson, 1994). From my perspective, asking participants about distance in meters is a clear case of elementarism. Elementarism is an approach that arises when elementary variables of the descriptive systems are also taken to be elementary of the system to be described. In Jacobs and Michaels' (2007) words:

"The breakaway from elementarism implies that learning to perceive properties that appear simple to the scientist might, in fact, be more difficult than learning to perceive properties that do not appear simple" (Jacobs & Michaels, 2007, p. 323)"

Michaels and Carello (1981) gave an elegant description of a typical application of this view in traditional psychology, when analyzing the concept of space perception:

> Thus, rather than asking how one perceives the positions of objects relative to each other and relative to the perceiver, traditional psychology encourages our asking how the dimensions required for this geometric description of position are perceived. (Michaels & Carello, 1981, p. 10)

This reasoning against elementarism illustrates that ecological psychology is somehow redeveloping a solution to the problem that the Gelstalt psychologists referred to as the 'bundle-hypothesis'. Briefly, the bundle hypothesis defines perceptual experience as collections of sensations, understood as some kind of molecular identities, separable from each other, and independently measurable. Following Käufer and Chemero (2015), it is easy to understand why Gelstalt psychologists—who focused on the explanation of the perception of whole patterns—reacted against the key idea of Wundt's psychology by which experience is a composition of simple sensations.

In fact, Koffka (1922) understood that the idea of the bundle hypothesis was applied not only to stimuli, but also to the so-called reactions to them. As Koffka commented, all psychologists (even behaviorists) built their models for explaining both sensation and reaction "joining reflex arcs to reflex arcs entirely in accordance with the method of the 'bundle-hypothesis'.", in the sense that was introduced in Chapter 2. In summary, elementarism inherits the rationale of the bundle hypothesis and, with this, it actualizes its main ideas. Ecological psychology reacts to elementarism in the same way as Gestaltists reacted to the bundle hypothesis. Thus, the main problem of maintaining the bundle hypothesis is clear in the case of the ecological approach: If perception is the bundle of discrete sensations, the agential dimension of the perceiver is dismissed, the perception-action loop is broken, and affordances cannot be the objects of perception.

Underlying the tradition of elementarism is the assumption that the same vocabulary that we use for explaining the physical world is equally useful for explaining perception. But, as Runeson, Juslin, and Olsson (2000) stated, each subdomain of science requires a vocabulary or conceptual system that identifies entities and properties that are essential to the phenomenon that is studied. If not, we run the risk of using arbitrary descriptions imposed by the researcher while we forget the importance of the level of description (Ibáñez-Gijón, 2014). In the case of the ecological scale, affordances are key in that system. Coming back to the study of Maidenbaum, Hanassy, et al. (2014) that guided this part of the discussion, the possibilities of a new device to substitute vision should not be related to the ability of participants to report verbally the distance in meters, but to their possibilities for action with the system. This type of non-elementaristic approach can very well be followed by researchers who are unrelated to ecological psychology, just because they are considering what is really relevant for an individual that needs to substitute one perceptual system by another. An example is the research reported by Kolarik, Timmis, Cirstea, and Pardhan (2014). These authors aimed to test the abilities of the central nervous system to use a SSD. Participants passed through apertures of different sizes, adjusting the shoulder rotation to pass effectively. No mention of the term 'affordance' was made, but the study was nevertheless consistent with the ecological emphasis on body-scaled information as well as with the focus on properties that are relevant to participants.

8.2.5 The Contribution of Active Exploration

Along this dissertation, the role of active exploration has been commented many times (Chapter 3, section 2.2.1, etc). Exploring implies a perception-action process that is intentionally directed during a period of time. The most important critique on SSDs with active exploration is that the exploration may be time-consuming (Borenstein, 1990). One result discussed in this dissertation clearly illustrates this point: In Chapter 5, Experiments 1a, 1b, and 1c resulted in different means for the variable trial duration when more active (Experiments 1a and 1c) and less active (Experiment 1b) orientation experiments were conducted. In Experiments 1a and 1c, where there was an on-line perception-action coupling, the absolute errors were smaller than the areas of sensitivity of the actuators. On the contrary, in Experiment 1b, where there was no on-line perception-action coupling, the average absolute error were five times higher than the sensitivity of actuators. These experiments revealed that the orientation without perception-action coupling showed less exploration and was less time-consuming than the orientation with perception-action coupling, but the absence of the exploration had a substantial negative effect on accuracy.

As argued in that same chapter, the documented oscillations provide a contribution in addition to previous research that supported that active exploration and perception-action couplings are important features of SSDs (see Auvray, Hanneton, & O'Regan, 2007, and Faugloire & Lejeune, 2014, for example). Oscillation, as a way of exploration, is time-consuming, but it allows the detection of information with high levels of precision. Lenay et al. (2003) mentioned similar results, with errors, below the sensitivity of the matrix of actuators, and they recognized this as hyperacuity. In their reasoning, this phenomenon is also due to the sensory-motor couplings allowed by the SSDs. Faugloire and Lejeune (2014) reported another case of hyperacuity (to a large extent replicated in Experiment 1c of Chapter 5).

8.3 Limitations and Future Work

As argued at the beginning of this dissertation, touch is in some sense the most essential perceptual system for humans. Along this dissertation we have seen the relatively unexplored possibilities offered by touch, such as detecting haptic expansions and providing hyperacuity. In contrast to the opinion of Spence (2014), which we saw in Chapter 5, page 97, results presented in this dissertation should encourage researchers to use touch as substitution of vision. In this section, I will address some limitations of the research presented in this dissertation and present possible research lines that could cope with those limitations.

Chapter 3 mentioned a limitation that needs to be considered (at least in part) in subsequent studies. In that chapter, it was claimed that "we do not have more precise knowledge about the informational variables that are used by novices and by experts and about how these variables are detected." As mentioned in subsection 8.2.2, a possible future research line would consist in studying the information usage for users of SSDs and to apply the obtained knowledge about information usage to derive training methods. In this search based on the specificity of the information, one possibility is to focus on how we can have an equivalent to optic flow in the haptic domain. As well as implementing and testing haptic flow equivalents of optic flow variables, the aim of such a project should be to apply, in research on sensory substitution, the methodology to identify variables that are used and, also, to design training methods that ecological psychologist have developed in the optical domain. In this vein, in Chapters 5 and 6, the challenge of describing examples of haptic flow just started.

As I commented in Section 8.1, in Chapter 6 it was not in fact optimal to directly compare the results of the blind participants with the results of the participants of Chapter 5 because the former ones were significantly older. It would be interesting to have a group of adults with regular vision and a similar age as the group of visually-impaired participants. I would like to highlight that the mere introduction of a SSD involves new sensorimotor contingencies that participants need to establish. In Chapter 7, participants in the V+ET condition had significant increments in trial duration compared to participants in the V condition. I interpret this result as the effect of participants paying attention to the new device and trying to establish contingencies; a task in which mobility could be playing a role. I cannot discard that blind participants of Chapter 6 had more problems for establishing sensorimotor contingencies merely because of the level of mobility associated to their older age.

If we think of increasing the complexity of the tasks described in this dissertation, the next logical steps should be to solve navigation tasks avoiding multiple dynamic obstacles and steering to dynamic targets just using vibrotactile information. From the perspective of affordances, we saw in Chapter 4, we could integrate body-scaled and action-scaled affordances (Fajen et al., 2008) including, for example, catching fly balls, passing under a barrier, and fitting the hand through an aperture.

With regard to the populations that might benefit from improvements in SSDs and from a more extended use of SSDs in everyday life, we should mention the deafblind population. In particular, children with congenitally deafblindness may extend their use of touch to obtain distal information. Besides visually-impaired people, firefighters, and pilots, they are the population that could benefit the most from technologies that increase personal autonomy.

Although speculative, I should mentioned in this section on future research that the four special-purpose SSDs in this dissertation were designed and chosen with the idea in mind that future versions of the devices may be used in a complementary fashion. For example, it may be useful to use the lower-leg device presented in Chapter 3 to control stepping actions with regard to nearby ground-level obstacles, such as edges of side walks, while using the vertical SSD on the chest presented in Chapter 4 to detect the presence or absence of such obstacles, while walking, from a slightly larger distance. Concurrently, the horizontal SSD with several rows of actuators on the waist presented in Chapter 5 may be used to detect and avoid yet slightly more distant vertical objects, such as fellow pedestrians or walls of a corridor. Finally, if needed, a hand held device similar to the one tested in Chapter 7 may serve to further inspect any of these action-relevant properties. In sum, rather than aiming to achieve a general-purpose sensory substitution, I believe that research programs on sensory substitution should work toward well-chosen and well-designed combinations of special-purpose devices, together with the relevant training programs.

8.4 Conclusions: a Change in Research on Sensory Substitution

In this dissertation, I adopted an approach that offers a set of resources with a high usability for sensory substitution. Despite the advantages of ecological psychology in real-world tasks, technology, and perception-action processes, an ecological approach to sensory substitution had been relatively unexplored. On the empirical side, this account allows us to design innovative devices from an informational point of view. This conclusion shares the rationale expressed in Ibáñez-Gijón, Díaz, Lobo, and Jacobs (2013) in the case of robotics, another field related to technology in which a change of paradigm could be beneficial. As we saw in Chapter 6, the ecological approach to sensory substitution has actual applications for people who have a visual impairment and it could also have applications for professionals who on ocassions to work in low-vision conditions, such as firefighters or pilots. The ecological approach provides us with a framework to test the use of SSDs in everyday tasks. On the theoretical side, some aspects included in this dissertation can be considered as encouraging contributions in a broader sense: They affect the mode in which we put together the different pieces for understanding human cognition. This is shown in several parts in this document, from the specific mentions about perception-action and learning processes in Chapter 3 to the questions about mental representations in Chapter 7 .

When talking about technology for visually-impaired individuals, the work of Bach-y-Rita and his colleagues is typically described as pioneering in the field. Probably, the work presented here has more in common with the ideas presented in 'Seeing with the skin' (White et al., 1970) than with the ideas presented in 'Seeing with the brain' (Bach-y-Rita et al., 2003). Taking this research from the late sixties and early seventies into account, it could be argued that the research presented in this dissertation is outdated. I do not think this is the case. Recently, the number of SSDs that share main features with the SSDs presented in this dissertation has been growing. Even when there is no explicit mention to sensorimotor, enactive, or ecological approaches, there are progressively more researchers who conduct experiments that involve agents (and not passive subjects) engaged in relevant tasks, often closely approximating real-world tasks. Consequently, to achieve progress in sensory substitution the idea that blind people cannot have autonomous navigation as long as they do not have a mental map, often imagined from a top-view, should be abandoned. In my opinion, it seems more reasonable to test the effectivity of SSDs using the devices in the real-world tasks rather than, for example, by asking participants to draw a map after wearing or using the device (see Maidenbaum et al., 2014, for an example of map drawing).

Technology for the visually-impaired people, as a part of a broader field of human-computer interaction, would benefit from adopting an ecological account. In a recent paper about Augmented Reality (AR, Raja & Calvo, 2017), the authors proposed a different way to build technology that I think it is a way to break away from the problem of constructing technology from the computer metaphor (section 8.2.4). They claimed: "Augmenting reality, we contend, is equivalent to constructing a niche: altering the environment permits the pick-up of new affordances." (Raja & Calvo, 2017, p. 71). Coming back to the very idea of humans as living beings in a niche is useful for sensory substitution, too. The only difference, in my opinion, is that in sensory substitution we are not constructing a niche as in it is the case of AR, but making detectable the information to perceive affordances that are, in fact, detectable if we were using another perceptual system. This is the reason why I chose the opening quotation of J.J. Gibson in this dissertation. His comment is inspiring for sensory substitution because he clarifies that, when we are perceiving an affordance, all perceptual systems detecting the information are equivalent—the exciting idea that has guided this dissertation!

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Capítulo 8

Discusión general y conclusiones

8.1 Resultados principales

Esta tesis doctoral se centra en la utilidad de la aproximación ecológica para el campo de la sustitución sensorial. En esta sección discutiré los resultados principales obtenidos de los cinco estudios descritos en los capítulos 3 a 7.

En el capítulo 3 el objetivo era saber, primero, si un SSD háptico colocado sobre la espinilla sería útil para detectar y pisar en obstáculos al nivel del suelo. Los resultados del experimento mostraron que los participantes eran capaces de realizar la tarea y, además, varios de estos participantes tenían una ejecución muy exitosa no solamente con respecto a la distancia hasta el obstáculo, sino con respecto a su altura. El segundo objetivo de este estudio era investigar el papel de la práctica y el entrenamiento con el SSD. Los resultados indicaron que los participantes mejoraron su ejecución desde la fase de pretest a la fase de postest. Curiosamente, los resultados revelaron que el rango de la inclinación de la espinilla cuando un participante está a punto de pisar un obstáculo es mayor después de practicar con el SSD. Finalmente, con respecto al tercer objetivo, los resultados revelaron una mejora significativa del grupo que entrenó sin visión. Cuando los participantes entrenaron sin visión, el rango de inclinación justo antes de pisar se incrementó significativamente más que el rango de aquellos participantes que entrenaron con visión.

En el capítulo 4, el principal objetivo era comprobar si los SSDs permiten la detección de affordances. La razón fundamental era que la sustitución fidedigna debe permitir a los usuarios la percepción de las propiedades relevantes del sistema organismo-entorno. La percepción de affordances con un SSD demostraría un correcto funcionamiento del dispositivo. Los resultados de este experimento mostraron que los participantes sí percibían las affordances. Las diferencias en la proporción de los escalones juzgados como escalables entre grupos de participantes altos y bajos desaparecieron cuando los datos se re-escalaron usando la ratio de la altura del escalón entre la longitud de la pierna de un participante. La altura máxima que un participante puede escalar con respecto a su pierna (i.e., el pi-number crítico) no se encontró que difiriese del pi-number crítico cuando la tarea se realizaba usando la visión (Warren, 1984). La única diferencia encontrada con resultados previos en juicios de escalabilidad con visión (Warren, 1984) fueron los límites de la curva de respuesta, que no alcanzaban el 0 % y el 100 % en nuestro caso. Esto está relacionado con una menor precisión de los usuarios del SSD en comparación con el uso de visión normal.

Como se mencionó en el capítulo 1, la lógica fundamental que subyace a este capítulo es comparar las affordances en dos modalidades perceptivas cuando, hasta la fecha, solo en una de ellas hay todavía dudas de atribución distal. Ha habido una gran discusión sobre si las usuarias perciben los objetos y los eventos como estando "ahí afuera" o si solo son conscientes de la estimulación de la piel, siendo incapaces de hacer una atribución distal cuando usan un SSD. En el experimento descrito no hay preguntas explícitas para los participantes sobre atribución distal. En lugar de eso, el mismo experimento que se usa en percepción visual se propone con un SSD. Cuando una persona juzga un escalón como escalable, casi nunca hay una sospecha de que sea solo consciente de su estimulación retiniana. La usuaria percibe el escalón como estando "ahí afuera": maneja el objeto como un objeto del mundo y lo juzga como escalable o no. El mismo razonamiento guía la percepción de affordances con un SSD: si la usuaria percibe la affordance no deberíamos dudar de su atribución distal.

En el capítulo 5 he presentado una versión sofisticada de anteriores dispositivos que mejoró la traducción de información óptica a información háptica. Este estudio tenía como objetivo saber cómo los usuarios detectaban información específica para propiedades del entorno. Se espera que este conocimiento pueda ser útil para extender el uso de SSDs y ETAs en la vida diaria. En este capítulo se realizaron cinco experimentos resolviendo tres tareas: orientarse, aproximarse y dirigirse hacia un objetivo. Los participantes fueron capaces de resolver todas las tareas con éxito.

Con respecto a la orientación, los participantes en el Experimento 1a tuvieron un error absoluto de 1.4º con áreas de sensibilidad de los actuadores de 2.5º. En el Experimento 1b tuvieron un error absoluto de 12.4º con las mismas áreas de sensibilidad de los actuadores, pero sin un acoplamiento perceptivo-motor on-line. Finalmente, en el Experimento 1c, los participantes tuvieron un error absoluto de 12.3º (similar al Experimento 1b) con un acoplamiento perceptivo-motor on-line pero con áreas de sensibilidad de los actuadores de 45º, 18 veces mayor que las del Experimento 1b. Las oscilaciones documentadas en estos experimentos muestran la efectividad del movimiento exploratorio para detectar información útil cuando puede establecerse un acoplamiento sensoriomotriz.

Con respecto al Experimento 2, los participantes pararon de media 5.9 cm por delante del borde del objetivo; esto es, cuando los actuadores más alejados del centro cuerpo se apagaban. En dos tercios de los ensayos se observó que los participantes se pasaban de largo del objetivo y volvían hacia atrás. Esto puede interpretarse como el resultado de que los participantes comprobando el acoplamiento sensoriomotriz. Comparando los resultados con los proporcionados por Loomis y col. (1992), el control on-line con este SSD es mejor que el control basado en ver primero un objetivo y acto seguido dirigirse hacia él sin verlo. Con el control háptico on-line, los participantes tenían una reducción del 71 % en el error absoluto.

En el experimento 3, los participantes tenían que dirigirse a un objetivo en una combinación de las tareas 1 y 2. Todas las funcionalidades del SSD estaban activadas durante esta tarea. El SSD vibrotáctil permitía detectar la información usada en la locomoción visual guiada (Fajen y Warren, 2003). La dirección del objetivo con respecto al cuerpo (θ) se indicaba usando la localización de la vibración en el abdomen de los participantes y la distancia entre participante y objetivo se indicaba usando la intensidad y el tamaño de los actuadores activos, permitiendo por ello la detección de “expansiones hápticas” y dando acceso a variables de tipo τ . En el 98.8 % de los ensayos, los participantes alcanzaron el objetivo exitosamente y tuvieron un error absoluto promedio de 37.1 cm, lo que significa que estaban 27.1 cm más adelantados del borde del objetivo. Se observaron también oscilaciones exploratorias en esta tarea.

En el capítulo 6 vimos un ejemplo de aproximación hacia un objetivo con personas con discapacidad visual. El objetivo de este capítulo era estudiar el SSD anterior con participantes con ceguera. Recordemos que los participantes en el capítulo 5 eran participantes con los ojos tapados que tenían visión normal, así que para ellos la expansión de un objeto en su campo visual era el modo natural de detectar la aproximación de un objeto. Comprobar este dispositivo con personas con ceguera resultaba extremadamente interesante ya que estos participantes no dependen de expansiones. Los resultados de este experimento mostraron que en el 97.2 % de los ensayos los participantes alcanzaban el objetivo y tenían un error absoluto promedio de 67.9 cm, esto es, 57.9 cm más adelantados que el borde del objetivo. Aunque esto es una diferencia significativa con respecto al error absoluto realizado por los participantes en el anterior capítulo, no interpreto esto como una consecuencia del período en el que comenzó la privación visual. Los participantes en este experimento eran significativamente mayores que los participantes del capítulo 5, lo que puede haber propiciado más problemas de movilidad. En mi opinión, es importante destacar que los participantes con discapacidad visual pudieron usar información vibrotáctil para detectar y alcanzar un objetivo de 10 cm (i.e., un objeto con un área de 314 cm^2) en un área de exploración de 500 × 700 cm, (i.e., un área de 350000 cm^2, más de mil veces mayor que el objetivo) en aproximadamente 34 segundos.

En el capítulo 7 se persiguieron dos objetivos. El primer objetivo era determinar si era posible solucionar una tarea de navegación compleja con un SSD minimalista. El segundo objetivo era saber si la navegación con el SSD podría explicarse sin apelar a representaciones mentales. El disopsitivo minimalista que se usó fue la Enactive Torch, un dispositivo que se lleva en la mano y que se puede dirigir para explorar. Tiene un único actuador que vibra en función de la distancia a los objetos. Considerando el primer objetivo, la Enactive Torch es útil para evitar obstáculos. Aun así, en mi opinión (y en contra de la idea intuitiva de los dispositivos minimalistas), la precisión en la ejecución se beneficiaría de un número mayor de actuadores, así como de un mayor rango espacial de detección (el rango de detección se discute en Nordbeck y Raja, 2015).

Considerando el segundo objetivo, se presentaron tres modelos distintos para explicar la navegación con SSDs. Dos de estos modelos afirman que la navegación requiere de planificación y representaciones espaciales. Las representaciones espaciales serían amodales de acuerdo con uno de los modelos visuales de acuerdo con el otro. Una tercera aproximación es la ofrecida por la aproximación del control basado en la información. La planificación es irrelevante para esta tercera aproximación. El uso de un dispositivo vibrotáctil de rango corto permitió poner a prueba este modelo alternativo (el del control basado en la información), que no necesita incluir representaciones mentales. La característica principal de este SSD es que no provee al usuario con una visión general de la configuración, sino con información egocéntrica de los obstáculos en un rango corto (1.5 m). Los resultados de nuestro experimento mostraron que los participantes no solamente completaban la tarea usando un SSD minimalista, sino que no hubo diferencias significativas en la selección de rutas entre los participantes que usaron el SSD y los participantes que usaban visión (reducida). Así, la aproximación alternativa propuesta por el control basado en la información satisface los requisitos para explicar no solo la locomoción guiada visualmente sino también la navegación con un SSD minimalista.

8.2 La aproximación ecológica a la sustitución sensorial: un desafío a la aproximación cognitivista

Desde una perspectiva global, los resultados de los experimentos anteriores desafían a la aproximación cognitivista. En esta sección discutiré cinco temas en los que difieren la aproximación ecológica y cognitivista. Estos temas son el papel de las representaciones mentales, el efecto del aprendizaje, la relevancia de la sensibilidad cutánea, la importancia de la especificidad de la información y la contribución de la exploración activa.

8.2.1 El papel de las representaciones mentales

En los capítulos 3 y 7 he presentado dos experimentos que afectan el debate sobre representaciones mentales. Se ha defendido que las representaciones mentales son necesarias para tener una correcta percepción del espacio y que, como consecuencia, los ciegos congénitos no pueden realizar las tareas al mismo nivel de las personas con ceguera tardía. Un ejemplo es el trabajo de Rieser y col. (1992). Estos autores argumentaron que aquellos individuos que tienen una historia de visión normal y la adquisión tardía de una discapacidad visual eran más sensibles a la información no visual sobre la estructura espacial que los ciegos congénitos o aquellos que eran ciegos tempranos. Revisiones posteriores, como las de Schinazi y col. (2016) y Thinus-Blanc y Gaunet (1997) minimizan el impacto de los resultados obtenidos por Rieser y col. (1992) comparados con la mayoría de estudios, que defendían casi lo opuesto.

En el capítulo 3, los beneficios del entrenamiento sin visión pueden discutirse desde el punto de vista de las representaciones visuales. Recordemos que los participantes en este experimento no tenían experiencia previa con SSDs y que tenían visión normal, lo que implica que siempre detectaban y escalaban escalones usando la visión. Los resultados de este experimento mostraron que los participantes que entrenaban con visión tenían una peor ejecución detectando el escalón que los participantes que entrenaban sin visión. Podría defenderse que los participantes en la condición con visión asociaban la estimulación visual con la estimulación vibrotáctil mientras realizaban la tarea en las sesiones de entrenamiento. Entonces, durante la fase post-test, solo tendrían que usar la estimulación vibrotáctil para representarse visualmente la tarea. Pero, si las representaciones mentales tuvieran un papel en esta tarea, deberíamos haber sido capaces de ver una mejora de la ejecución de aquellos que pueden relacionar la visión con la estimulación vibrotáctil. Por el contrario, observamos que la exploración para detectar variables relevantes con el dispositivo vibrotáctil no es óptima cuando la tarea se resolvía previamente usando la visión. Tales resultados cuestionan la hipótesis de que las representaciones visuales son necesarias para establecer un paralelismo en sustitución sensorial. Más bien al contrario, parece que la visión evitaba que los usuarios dependiesen, al menos en parte, de la información vibrotáctil.

Debido a las condiciones experimentales, la extensión de la discusión sobre representaciones mentales en el capítulo 3 concierne únicamente al papel de las representaciones visuales. Sin embargo, en el capítulo 7, presenté un experimento que va más allá de las representaciones visuales y discute el asunto de las representaciones mentales en general. Encontramos que el uso de las representaciones mentales, incluso cuando hablamos sobre representación amodal, es muy improbable en la selección de rutas. En este estudio, las condiciones experimentales del grupo de participantes que usaron el SSD evitaba que planeasen una ruta. Dado que los resultados de este grupo no fueron diferentes de aquellos que teóricamente podían planear una ruta, se descarta la necesidad de representaciones espaciales. ¿Significa esto que no usamos representaciones mentales para la selección de rutas? Como se defendió en el capítulo 4, las afirmaciones sobre la percepción directa con SSDs están siempre abiertas a las críticas de los escépticos. Sin embargo, postular representaciones mentales no es la explicación más parsimoniosa; en el capítulo 7, en contraste, se ofrece una explicación más parsimoniosa.

Desde el punto de vista experimental, las decisiones metodológicas no son neutrales con respecto a la aproximación teórica que se adopta. Los experimentos presentados en esta tesis doctoral proponían tareas relevantes para los agentes, en contraste con lo que ha sido relativamente común en la literatura; esto es, diseñar tareas que consideran a los participantes como sujetos pasivos cuyos procesos cognitivos están basados en representaciones. El problema de considerar a los participantes como sujetos pasivos que computan representaciones es parte del círculo vicioso de la metáfora del ordenador. En mi opinión, el círculo vicioso procede de la siguiente manera: tendemos a usar esta metáfora para explicar que la mente humana funciona como un ordenador; entonces, tendemos a construir tecnología para la gente—imaginemos por ejemplo un SSD—basada en explicaciones de cómo la mente funciona de acuerdo con la metáfora anteriormente citada y, finalmente, probamos a la gente usando tecnología que construimos como si estuviéramos probando un ordenador. La psicología ecológica reacciona contra la idea de los participantes como sujetos pasivos. En su lugar, esta aproximación propone que la cognición se explica apelando al acoplamiento de los organismos activos con sus entornos.

8.2.2 El efecto del aprendizaje

Considerando los errores, los resultados en el capítulo 3 revelaron que los participantes en la condición de no-visión aprenden cómo usar el dispositivo mejor que en la condición de visión. En este capítulo también vimos que ambos grupos de entrenamiento reducían igualmente la duración de los ensayos. Es notable que la reducción de la duración del ensayo ocurrió a pesar del hecho de que el grupo de no-visión incrementó significantemente el rango de inclinación antes de la pisada. Por ello, desde la perspectiva del proceso de aprendizaje, la mejora de la ejecución observada se relaciona con una intensificación de los movimientos exploratorios en un sentido muy específico. Una posible interpretación de este resultado es que el aprendizaje no necesariamente conlleva una reducción en la exploración, sino una optimización de esa exploración. En la literatura de sustitución sensorial, ha sido común usar la duración del ensayo como una medida del aprendizaje a expensas de otras medidas cuantitativas (Faugloire y Lejeune, 2014). De los datos presentados aquí puede defenderse que el acoplamiento sensoriomotriz contiene información clave para mejorar la ejecución y que deberían estudiarse las variables de movimiento y no solo las variables de ejecución.

Mi interpretación es que los problemas de entrenamiento deberían basarse en la teoría del aprendizaje directo (Jacobs y Michaels, 2007; cf. Smeeton, Huys y Jacobs, 2013). Con ese marco podríamos diseñar programas en los que se manipula la utilidad de las variables para percibir una propiedad. Podríamos acelerar el proceso de aprendizaje de novatos a expertos con programas que puedan ser adaptados a cada usuario. Como se describió en el capítulo 2, las invariantes que se sabe que son usadas se necesitan para presentar el espacio y el movimiento de un usuario en ese espacio. Un trabajo posible en el futuro podría estar dirigido al estudio de las invariantes perceptivas que son importantes en la sustitución sensorial y su uso para diseñar un programa de entrenamiento.

8.2.3 La relevancia de la sensibilidad cutánea

La sensibilidad cutánea ha sido un tema importante en la literatura de sustitución sensorial. Por ejemplo, el desarrollo del TDU (capítulo 2) después del TVSS estaba basado en la idea de que las superficies receptoras deben ser muy sensibles para ser útiles para la sustitución sensorial (Bach-y-Rita y col., 2003). Aunque el debate sobre la sensibilidad de las diferentes áreas en contacto con SSDs no ha sido directamente estudiado en esta tesis doctoral, es destacable que los participantes encuentren útiles dispositivos que se llevan en la espinilla, el pecho y el abdomen. Desde una perspectiva cognitivista, la lengua sería un mejor lugar que la pierna para usar un dispositivo vibrotáctil (véase, por ejemplo, la reflexión sobre la sensibilidad espacial en Spence, 2014). Sin embargo, la importancia de la sensibilidad podría estar sobreestimada teniendo en cuenta la importancia de los acoplamientos on-line. En esta tesis doctoral, el uso de la pierna, el abdomen, el pecho y la mano permitió la exploración con la mismo área que estaba en contacto con la estimulación novedosa, de modo que los usuarios pudieron explotar fácilmente los nuevos acoplamientos sensoriomotrices.

Los resultados de los capítulos 5 y 6 (y los tests realizado por Cancar, Díaz, Barrientos, Travieso y Jacobs, 2013) sugieren que los participantes podrían usar expansiones hápticas para detectar la aproximación de un obstáculo y su tiempo de contacto. Para usar expansiones necesitamos aumentar el número de tactores. Debido a este incremento y al tamaño estándar de los actuadores señalados en esta tesis, el uso de una superficie cutánea mayor que las normalmente propuestas (manos, mejillas, frente y el primer dedo del pie; véase Kandel, Schwartz y Jessell, 2000, para una comparación con otras áreas) fue casi inevitable. En contraste con el cambio hecho por Bach-y-Rita y sus colaboradores descartando el TVSS a favor del TDU (o el Brainport) por la sensibilidad de la lengua (véase Bach-y-Rita y Kercel, 2003), mi propuesta es incrementar la cantidad de actuadores incluso si eso significa dar menos importancia a la sensibilidad de la piel. haciendo eso, podríamos tener una estructura en la cual las variables de alto orden puedan detectarse.

Además de la importancia de explorar con la misma área que está en contacto con el SSD y la necesidad de áreas más grandes para un alto número de actuadores que he comentado en párrafos previos, otra razón que reduce la relevancia de la sensibilidad cutánea puede plantarse: las mediciones habituales se hacen de manera pasiva. La primera razón para la baja aplicabilidad de los SSD que era consideraba en el capítulo 5 era precisamente la baja sensibilidad de la piel. Sin embargo, parece que los participantes en el Experimento 1a podían sentir la vibración con una diferencia por debajo de 1 cm en el abdomen cuando la tarea se realizaba de modo activo. Eso significa al menos un 66 % de reducción con respecto al umbral de los dos puntos descrito por Weinstein (1968). Esta medida, que ha sido clásicamente usada en estudios sobre sustitución sensorial, podría ser menos relevante que lo que ha sido afirmado por Giudice y col. (2014) o Kercel y Bach-y-Rita (2006), por ejemplo.

8.2.4 La importancia de la especificidad de la información

En la sección 2.2.4 he discutido la importancia de identificar cuáles son las variables específicas para realizar una tarea en relación con el proceso de aprendizaje. Una aproximación complementaria a la información se describe en el capítulo 5. En este conjunto de experimentos, el SSD proveía de análogos hápticos de variables que son relevantes para la locomoción guiada visualmente (Fajen y Warren, 2003). Lo más importante de esta variable es la dirección del objetivo con respecto al cuerpo, que era percibida a través de la localización de la vibración del SSD. La importancia de las invariantes perceptivas es clave en la explicación de la percepción por la psicología ecológica, porque la percepción de las affordances es el resultado de la detección de la información (véase la cita de Richardson y col., 2008, en el capítulo 2). Una psicóloga ecológica, entonces, se dirige típicamente a responder la pregunta de cuál es la información que especifica la affordance y si esa información en realmente detectada.

El estudio descrito en el capítulo 4 es un buen ejemplo de cómo la detección de información relevante lleva a la percepción de una affordance. Otro ejemplo puede encontrarse en el capítulo 2. En la sección 2.2.3 usé el término tacto dinámico para introducir un paradigma experimental que relaciona el momento de inercia de una varilla (o el tensor de inercia cuando la varilla se blande en tres dimensiones) con la longitud percibida de la varilla como un ejemplo de la información específica. Otro ejemplo bien conocido de información especifica, más relacionado con la navegación, es la variable τ, que es el tamaño angular de un objeto en nuestro sistema visual dividido por su propia derivada. Esta variable ha sido útil en muchos experimentos después de la descripción original de la variable en el estudio sobre el comprotamiento de los alcatraces hecho por Lee y Reddish (1981). La variable τ es específica del tiempo de contacto bajo algunas circunstancias. Un razonamiento paralelo lleva al diseño del dispositivo usado en los capítulo 5 y 6. Creo que la aproximación seguida garantiza la relevancia de las variables consideradas de flujo háptico, porque estas variable son 'traducciones' relativamente directas de variables de flujo óptico que son conocidas por ser relevantes para la locomoción guiada visualmente.

Sin embargo, la descripción de lo que es relevante para un usuario no está exenta de controversia. Atendiendo a algunos de los experimentos que comprobaban el correcto funcionamiento de nuevos dispositivos, parece que informar de las propias posibilidades para la acción con un dispositivo SSD es menos relevante que informar de la percepción de otras variables más 'elementales'. Este asunto puede ilustrarse con el estudio de Maidenbaum, Hanassy y col. (2014). En esta investigación se realizaron tres experimentos, aunque solo me centraré en el primero.

En ese estudio, los experimentadores pidieron a los participantes que informasen verbalmente de la distancia que había hasta una hoja de cartón localizada delante de ellos mientras usaban un SSD vibrotáctil y auditivo sujetado con la mano. Los autores informaron de que uno de los tres participantes ciegos de su estudio tenía grandes dificultades entendiendo el "concepto de distancia en metros" después de cinco minutos de entrenamiento. Este entrenamiento consistía en un experimentador sujetando la hoja de cartón para dar a los participantes "una sensación de los diferentes outputs (por ejemplo, 'la hoja está ahora a dos metros de distancia, así es como se siente un objeto a esta distancia')" (Maidenbaum, Hanassy y col., 2014, pág. 816). Esto ocurrió usando incluso la misma localización de la hoja de cartón en los ensayos de familiarización y en los ensayos del experimento en sí. En esta situación, parece que una evaluación adecuada tanto de individuos con ceguera como de individuos con los ojos tapados debería depender de la percepción de affordances más que de la distancia a los objetos en metros.

Nótese que he usado la misma palabra, relevante, para explicar la aproximación de los capítulos 4 y 5 al principio de esta subsección. En el marco ecológico, relevante tiene un sentido muy específico: algo es relevante cuando es significativo para las actividades e intereses del organismo (Runeson, 1994). Desde mi perspectiva, pedir a los participantes que informen sobre la distancia en metros es un caso claro de elementarismo. El elementarismo es una aproximación que surge cuando las variables elementales de los sistemas descriptivos también se toman como elementales del sistema que es descrito. En palabras de Jacobs y Michaels (2007):

"La ruptura con el elementarismo implica que el aprendizaje para percibir las propiedades que parecen simples al científico podría, de hecho, ser más difícil que el aprendizaje para percibir propiedades que no parecen simples (Jacobs y Michaels, 2007, pág. 323) "

Michaels y Carello (1981) hicieron una elegante descripción de la aplicación típica de esta visión en la psicología tradicional cuando analizaron el concepto de percepción del espacio:

> Así, más que preguntarse cómo uno percibe las posiciones de los objetos relativos a cada uno y relativos al perceptor, la psicología tradicional nos anima a preguntarnos cómo se perciben las dimensiones requeridas para esta descripción geométrica de la posición (Michaels y Carello, 1981, pág. 10)

Este argumento contra elementarismo muestra que la psicología ecológica está, de algún modo, re-desarrollando la solución al problema que los psicólogos de la Gestalt llamaron *hipótesis del haz*. De manera breve, la hipótesis del haz define la experiencia perceptiva como colecciones de sensaciones, comprendidas como algún tipo de identidades moleculares, separables unas de otras, y medibles de manera independiente. Siguiendo a Käufer y Chemero (2015), es fácil comprender cómo los psicólogos de la Gestalt (que se centraban en la explicación de la percepción de patrones completos) reaccionaron contra la idea clave de la psicología de Wundt por la cual la experiencia es una composición de sensaciones simples.

De hecho, Koffka (1922) entendía que la idea de la hipótesis del haz no solo se aplicaba a los estímulos, sino a las así llamadas reacciones a ellos. Como comentó Koffka, todos los psicólogos (incluso los conductistas) construían sus modelos para explicar tanto la sensación como la reacción “uniendo arcos reflejos a arcos reflejos enteramente en consonancia con el método de la ‘hipótesis del haz’.”, en el sentido introducido en el capítulo 2. En resumen, el elementarismo hereda la lógica fundamental de la hipótesis del haz y, con esto, actualiza sus ideas principales. La psicología ecológica reacciona contra el elementarismo del mismo modo en el que los Gestaltistas reaccionaban a la hipótesis del haz. Así, el principal problema de mantener la hipótesis del haz es claro en el caso de la aproximación ecológica: si la percepción es el haz de sensaciones discretas, la dimensión agencial de la persona que percibe se rechaza, el bucle percepción-acción se rompe y las affordances no pueden ser los objetos de la percepción.

Subyaciendo a la noción de elementarismo está la asunción de que el mismo vocabulario que usamos para explicar el mundo físico es igualmente útil para explicar la percepción. Pero, como afirmaron Runeson y col. (2000), cada subdominio de la ciencia requiere un vocabulario o sistema conceptual que identifique entidades y propiedades que son esenciales al fenómeno que es estudiado. Si no, corremos el riesgo de usar descripciones arbitrarias impuestas por el investigador mientras que olvidamos la importancia del nivel de descripción (Ibáñez-Gijón, 2014). En el caso de la escala ecológica, las affordances son clave en ese sistema. Volviendo al estudio de Maidenbaum, Hanassy y col. (2014) que guiaba parte de esta discusión, las posibilidades de un nuevo dispositivo para sustituir la visión no deberían estar relacionadas con la habilidad de los participantes para informar verbalmente de la distancia en metros, sino de las posibilidades para la acción con el dispositivo. Este tipo de aproximaciones no-elementaristas pueden ser perfectamente asumidas por investigadores que no están relacionados con la psicología ecológica, simplemente porque consideran qué es lo realmente relevante para un individuo que necesita sustituir un sistema perceptivo por otro. Un ejemplo es el trabajo de Kolarik y col. (2014). Estos autores intentaban probar la capacidad del sistema nervioso central usando un dispositivo de sustitución sensorial. En esta tarea, los participantes tenían que pasar a través de aperturas de tamaños distintos, ajustando la rotación de sus hombros para pasar de manera efectiva. No se hace mención del término 'affordance' en el estudio, pero es obvio para mí que tuvieron en cuenta información a escala corporal para centrarse en las propiedades relevantes para los participantes.

8.2.5 La contribución de la exploración activa

A lo largo de esta tesis doctoral, el papel de la exploración activa se ha comentado muchas veces (capítulo 3, sección 2.2.1, etc.). Explorar implica un proceso de percepción-acción intencionalmente dirigido durante cierto periodo de tiempo. La crítica más importante que recibe la exploración activa con un SSD es que la exploración consume tiempo (Borenstein, 1990). Un resultado discutido en esta tesis doctoral mostró de este punto de manera absolutamente clara: en el capítulo 5, los Experimentos 1a, 1b, y 1c resultaron en distintos medias para la variable duración del ensayo cuando se realizó un experimento de orientación activa (Experimentos 1a y 1c) y menos activa (Experimento 1b). En los Experimentos 1a y 1c, donde había un acoplamiento on-line perceptivo-motor, los errores absolutos eran menores que la sensibilidad de los actuadores. Por el contrario, en el Experimento 1b, donde no había acoplamiento on-line perceptivo-motor, el error absoluto promediado fue cinco veces mayor que la sensibilidad de los actuadores. Los resultados de este experimento sugerían que la orientación sin acoplamiento on-line perceptivo-motor puede consumir menos tiempo que la orientación con acoplamiento perceptivo-motor, pero la ausencia de un exploración tiene un efecto sustancialmente negativo en la precisión.

Como hemos visto en este mismo capítulo, las oscilaciones documentadas son una contribución innovadora a trabajos previos que afirman que los acoplamientos activos son rasgos importantes de los SSDs (véase Auvray, Hanneton y O'Regan, 2007, y Faugloire y Lejeune, 2014, por ejemplo). Estas oscilaciones, como un modo de exploración, consume tiempo pero permiten la detección de información con altos niveles de precisión. Lenay y col. (2003) mencionaron resultados similares con errores por debajo de la sensibilidad de la matriz de actuadores, y reconocieron esto como hiperagudeza. En su razonamiento, este fenómeno se debe al acoplamiento sensoriomotriz que permiten los SSDs. Faugloire y Lejeune (2014) mostraron otro caso de hiperagudeza (en gran medida replicado en el Experimento 1c del capítulo 5).

8.3 Limitaciones y trabajo futuro

Como se argumentó al principio de esta tesis doctoral, el tacto es el sistema perceptivo más esencial para los humanos. Y hemos visto a lo largo de esta tesis doctoral las posibilidades relativamente inexploradas que el tacto ofrece, tales como la detección de expansiones ópticas y la hiperagudeza. A diferencia de la opinión de Spence (2014) que hemos visto en el capítulo 5, página 97, los resultados presentados en esta tesis doctoral deberían animar a los investigadores a usar el tacto como un sustituto de la visión. En esta sección, me centraré en algunas limitaciones del trabajo presentado en esta tesis doctoral y en las posibles líneas de investigación que pudieran lidiar con esas limitaciones.

En el capítulo 3 se menciona explícitamente una limitación que necesita ser considerada (al menos en parte) en siguientes estudios. En ese capítulo se afirma que "no tenemos un conocimiento más preciso sobre las variables informacionales que son usadas por los novatos y por los expertos ni sobre cómo se detectan esas variables". Como se menciona en la subsección 8.2.2, una posible línea de investigación en el futuro consistiría en estudiar las diferencias en el uso de la información por usuarios de SSD y aplicar en conocimiento obtenido sobre el uso de la información para derivar métodos de entrenamiento. En esta búsqueda de la especificidad de la información, una posibilidad es centrarse en cómo podemos tener un equivalente a las variables de flujo óptico en el dominio háptico. Además de implementar y probar equivalentes del flujo óptico en el fluho háptico, el objetivo de tal proyecto seria aplicar en la investigación de la sustitución señorial la metodología para identificar variables que se usan para diseñar métodos de entrenamiento que los psicólogos ecológicos han desarrollado en el dominio óptico. En este sentido, en los capítulos 5 y 6, el desafío de describir ejemplos de flujo háptico solamente comenzaba.

Como he comentado en la sección 8.1, en el capítulo 6 no era, de hecho, óptimo comparar los resultados de los participantes con ceguera con los resultados de los participantes del capítulo 5, porque los primeros era significativamente más mayores. Sería interesante tener un grupo de adultos con visión normal y edad similar al grupo de participantes con discapacidad visual. Me gustaría destacar que la sola introducción de un SSD conlleva nuevas contingencias sensoriomotrices que los participantes necesitan establecer. En el capítulo 7, los participantes en la condición V+ET tenían incrementos significativos en la duración del ensayo comparados con los participantes en la condición V. Interpreto este resultado como un efecto de los participantes prestando atención al nuevo dispositivo e intentando establecer contingencias; una tarea en la cual la movilidad podría estar jugando un papel. No puedo descartar que los participantes del capítulo 6 tengan más problemas para establecer contingencias sensoriomotrices solamente debido al nivel de movilidad relacionado con una mayor edad.

Si pensamos en incrementar la complejidad de las tareas descritas en esta tesis doctoral, los próximos pasos lógicos deberían ser solucionar las tareas de navegación evitando múltiples obstáculos dinámicos y dirigirse a objetivos dinámicos usando solo la información vibrotáctil. Desde la perspectiva de las affordances, como vimos en el capítulo 4, podríamos integrar affordances de escala corporal y affordances de escala de acción (Fajen y col., 2008) incluyendo, por ejemplo, el atrapar pelotas voladoras, pasar debajo de barreras, y ajustar la mano a través de una apertura.

Con respecto a las poblaciones que podrían beneficiarse de las mejorad en SSDs y de una mejor distribución de los SSDs eb la vida diaria, deberíamos mencionar a la población sordociega. En particular, niños con sordoceguera congénita pueden extender el uso del tacto para obtener información distal. Además de las personas con discapacidad visual, bomberos y pilotos, ellos son la población que más podría beneficiarse de tener tecnologías que aumenten la autonomía personal.

Aunque es especulativo, debería mencionar en esa sección de líneas futuras de investigación que los cuatro dispositivos de propósito específico de esta tesis doctoral fueron diseñados y escogidos con la idea en mente de que futuras versiones de los dispositivos puedan ser usadas de una manera complementaria. Por ejemplo, puede ser útil usar el dispositivo para la parte baja de la pierna presentado en el capítulo 3 para controlar las acciones de pisada con respecto a obstáculos cercanos al nivel del suelo, tales como bordillos de aceras, mientras se usa el SSD vertical del torso presentado en el capítulo 4 para detectar la presencia o ausencia de tales obstáculos, mientras se camina, desde una distancia algo mayor. De forma concurrente, el dispositivo horizontal con varias filas de actuadores sobre la cintura presentado en el capítulo 5 puede ser usado para detectar y evitar objetos verticales ligeramente más distantes, tales como otro peatones, paredes, o un pasillo. Finalmente, si es necesario, un dispositivo para llevar en la mano similar al probado en el capítulo 7 puede servir para inspeccionar además alguna de las propiedades relevantes para la acción. En resumen, en vez de dirigirse hacia conseguir un dispositivo de sustitución sensorial de propósito general, creo que los programas de investigación en sustitución sensorial deberían trabajar en combinaciones bien escogidas y bien diseñadas de dispositivos de propósito específico, junto con programas de entrenamiento relevantes.

8.4 Conclusiones: Un cambio en la investigación en sustitución sensorial

En esta tesis doctoral he adoptado una aproximación que ofrece un conjunto de recursos con una alta usabilidad para la sustitución sensorial. A pesar de las conocidas ventajas de la psicología ecológica en tareas del mundo real, tecnología y procesos de percepción-acción, una aproximación ecológica a la sustitución sensorial había sido, hasta la fecha, bastante inexplorada. En la parte empírica, esta explicación nos permite diseñar dispositivos innovadores desde un punto de vista informacional. Esta conclusión comparte la la lógica expresada en Ibáñez-Gijón y col. (2013) en el caso de la robótica, otro campo relacionado con la tecnología en el que un cambio de paradigma podría ser beneficioso. Como hemos visto en el capítulo 6, la aproximación ecológica a la sustitución sensorial tiene aplicaciones reales para personas que tienen discapacidad visual, y también podría tenerla para profesionales que a veces necesitan trabajar en condiciones de baja visibilidad, como bomberos y pilotos. También nos provee con un marco para comprobar el uso de los SSDs en tareas cotidianas. En el lado teórico, algunos aspectos incluidos en esta tesis doctoral pueden considerarse como contribuciones alentadoras en un sentido más amplio: afectan al modo en que estamos uniendo las diferentes piezas para comprender la cognición humana. Esto se muestra en muchas partes de este documento, desde las menciones específicas sobre la percepción-acción y los procesos de aprendizaje en el capítulo 3 a las preguntas sobre representaciones mentales en el capítulo 7.

Cuando se habla de tecnología para las personas con discapacidad visual, el trabajo de Bach-y-Rita y sus colaboradores siempre aparece como pionero en el campo. Probablemente, el trabajo presentado aquí tiene más en común con las ideas presentadas en 'Ver con la piel' (White y col., 1970) que con las ideas presentadas en 'Ver con el cerebro' (Bach-y-Rita y col., 2003). Tomando en cuenta esta investigación desde los últimos años de la década de los sesenta y los primeros de los setenta, se podría argumentar que las ideas presentadas en esta tesis doctoral están atrasadas. No creo que este sea el caso. Recientemente, el número de SSDs que comparten rasgos principales con los SSDs presentados en esta tesis doctoral está creciendo. Incluso cuando no hay mención explícita a las aproximaciones sensoriomotrices, enactivas o ecológicas, hay progresivamente más investigadores que llevan a cabo experimentos que incluyen agentes (y no sujetos pasivos) en tareas bastante aproximadas a las tareas del mundo real. Consecuentemente, para progresar en sustitución sensorial debe abandonarse la idea de que las personas con ceguera no pueden tener una navegación autónoma en tanto que no tengan un mapa mental, frecuentemente imaginado desde una visión cenital. En mi opinión, parece más razonable comprobar la efectividad de un SSD usando el dispositivo mismo y no pedir a los participantes que dibujen un mapa después de llevar puesto o usar un dispositivo (véase Maidenbaum y col., 2014, para un ejemplo de dibujo de mapas).

La tecnología para la gente con discapacidad visual, como parte de un campo más amplio de la interacción humano-ordenador, se beneficiaría de adoptar una explicación ecológica. En un artículo reciente sobre Realidad Aumentada (AR, Raja y Calvo, 2017), los autores proponían un modo diferentes de construir tecnología que creo que es un modo de eliminar el problema de construir la tecnología desde la metáfora del ordenador (sección 8.2.4). Afirmaban lo siguiente: "Aumentar la realidad, afirmamos, es equivalente a construir un nicho: alterar el entorno permite la percepción de nuevas affordances" (Raja y Calvo, 2017, pág. 71). Volver a la misma idea de los humanos como seres vivos en un nicho es útil también para la sustitución sensorial. La única diferencia, en mi opinión, es que en la sustitución sensorial no estamos construyendo un nicho como en el caso de AR, sino haciendo detectable la información para percibir affordances que son, de hecho, detectables si estuviéramos usando otro sistema perceptivo. Esta es la razón por la que escogí la cita inicial de J. J. Gibson para esta tesis doctoral. Su comentario es inspirador para la sustitución sensorial porque clarifica que, cuando estamos percibiendo una affordance, todos los sistemas perceptivos para detectar la información son equivalentes—¡la emocionante idea que ha guiado esta tesis doctoral!

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Index

Appendix A

Published Articles

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Stepping on Obstacles with a Sensory Substitution Device on the Lower Leg: Practice without Vision Is More Beneficial than Practice with Vision

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Abstract

Practice is essential for an adapted use of sensory substitution devices. Understanding the learning process is therefore a fundamental issue in this field of research. This study presents a novel sensory substitution device worn on the lower leg and uses the device to study learning. The device includes 32 vibrotactile actuators that each vibrate as a function of the distance to the nearest surface in a particular direction. Participants wearing the device were asked to approach an object and to step on the object. Two 144-trial practice conditions were compared in a pretest-practice-posttest design. Participants in the first condition practiced with vibrotactile stimulation while blindfolded. Participants in the second condition practiced with vibrotactile stimulation along with normal vision. Performance was relatively successful, both types of practice led to improvements in performance, and practice without vision led to a larger reduction in the number of errors than practice with vision. These results indicate that distance-based sensory substitution is promising in addition to the more traditional light-intensity-based sensory substitution and that providing appropriate sensorimotor couplings is more important than applying the stimulation to highly sensitive body parts. The observed advantage of practice without vision over practice with vision is interpreted in terms of the guidance hypothesis of feedback and learning.

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Introduction

Sensory substitution devices are devices that transform ambient energy patterns typically associated to one sense modality into patterns that can be detected through another modality. Commonly used transformations are visual to auditory and visual to tactile. Sensory substitution devices raise important fundamental scientific questions, including questions related to brain plasticity [1] and sensorimotor theories [2]. The majority of the applications of sensory substitution devices are directed to visually impaired people [3], but other applications can be found in fields such as pilot navigation, balance control, speech comprehension, and other fields [4].

Some type of training with sensory substitution devices is beneficial or even necessary [5–7]. Lenay and colleagues [8], for example, argued that "even the most user-friendly device will inevitably require a substantial learning process" (p. 286). These authors further claimed that the availability of appropriate learning protocols is a crucial factor for the success of sensory substitution devices. In line with such claims, the main purpose of the here-reported experiment is to contribute to the understanding of learning with sensory substitution devices. In addition to noting the importance of learning, Lenay and colleagues [8] elegantly expressed several theoretical observations that are important for the design of sensory substitution devices, some of which are related to the ecological approach to perception [9].

From the ecological point of view, perception is the picking up of higher-order variables that are useful for goal-directed behavior. To give a few examples, often-studied higher-order variables include the focus of expansion of the optic flow as specification of the direction of movement, or texture gradients as specification of terrain orientation. The ecological approach considers perception and action as two sides of the same coin; both are part of a unique process of information detection. A large number of empirical studies support the role of exploratory movements in the detection of information. Prominent among these studies are the bodies of work on dynamic touch [10] and on the concept of *exploratory procedures* [11]. Given the importance of exploratory movements in the regular functioning of perceptual and perceptual-motor systems, it seems reasonable to expect that, in order to be effective, sensory substitution systems should allow exploratory movements and sensorimotor couplings, and thereby the detection of environmental information specific to action-relevant properties.

Inspired by the ecological framework, we have previously designed and constructed sensory substitution devices that transform distance-related information into vibrotactile patterns on the torso. We experimented with these devices using tasks that are among those most typically considered by proponents of the ecological approach: the perception of obstacles [12] and of time to contact [13]. The here-presented research continues this overall approach to sensory substitution. We designed a novel device that tranforms distance-related information into vibrotactile patterns on the lower leg. An experiment is reported in which participants use the novel device to step on ground-level obstacles. The purpose of the experiment is to respond to learning-related questions.

One of the first systematic investigations of learning in sensory substitution was performed with a device referred to as the *binaural sensory aid* [14]. This device associates the distance of a target to a pitch, and the direction to an interaural amplitude difference. In the experiment reported in [14], the perception of distance and direction with the device improved after a training phase in which users received haptic feedback by touching the targets. Learning effects have also been reported in [15] and [16]. In [15], the authors used vibrotactile stimulation applied to the left index finger of participants with an *Optacon* and observed learning in the absence of feedback. In [16], a visual-to-auditory device, referred to as *the vOICe* [17], was used and visual feedback was provided without motor interaction with the environment. In addition to these and other studies with laboratory tasks, learning effects have been reported after practice with more dynamic and arguably more natural interactions with objects [18] and after the prolonged and continuous use of substitution devices outside the laboratory [19,20].

In comparison to the large number of studies that demonstrate that learning occurs–with different devices, different tasks, and with different types of feedback as well as without feedback–few studies focus on factors that may facilitate or impair learning. Consider the following question: In learning to use a device that provides vibrotactile stimulation, what are the effects, if any, of the absence of vision during practice as compared to the possibility to rely on vision during practice? Proulx and colleagues [20] tested performance with a sensory substitution device (the vOICe) that was used during 21 days, either with or without vision. Their study, however, included only one participant in each of these conditions (as well as more participants in conditions that are not described here). Also relevant is an experiment reported in [21], in which participants learned to control a robot on the basis of tactile stimulation coupled to a camera placed on the robot. The experiment included practice phases with visual and tactile stimulation as well as practice phases with tactile stimulation only. Even so, because the purpose of the experiment was not to compare the different practice phases, all participants went through the phases in the same order, making an unbiased comparison impossible. Hence, more research is needed to understand the effects of the presence or absence of vision while learning to use non-visual sensory substitution devices.

To perform such research and to advance our broader research project, we constructed a sensory substitution device with 32 actuators on the frontal part of the lower leg. If a user stands straight up on a flat ground surface without obstacles, then all actuators vibrate with a (low) standard vibration. Deviations from this situation–which may be due to movement of the user or to the presence of an obstacle–lead to changes in the pattern of vibration. Each actuator vibrates as a function of the distance to the nearest surface in a particular sensing direction: the closer the nearest surface, the more intense the vibration. The so-computed patterns of vibration and the changes therein may allow users to perceive ground-level obstacles and to step on them. Our device does not include real sensors. Instead, to control the vibration of the actuators, the position of the lower leg is detected with movement registration cameras, and the distance to the nearest surface (either the floor or a box) is computed on-line on the basis of knowledge about the locations of the surfaces in the environment. In the reported experiment, participants wearing the device were asked to walk toward objects and to step on them.

In accordance with the issues raised above, the aims of our study are (a) to determine if it is possible to use our device to step on ground-level obstacles and, thereby, to confirm the usefulness of this type of device, (b) to determine if and how the execution of this perception-action task changes and improves with experience with the device, and (c) to determine if different practice conditions have different effects on performance. To test the effect of experience, we used a pretest-practice-posttest design with four 36-trial practice blocks. A first group of participants performed the practice blocks while blindfolded whereas a second group performed the practice blocks with vision.

Our analyses address the time needed to perform the task and several error measures: the number of trials on which the foot is lifted before reaching the obstacle, the number of trials on which the foot is not lifted sufficiently so that the obstacle is hit, and the sum of these errors. Also analyzed are the distance (from the box) at which the foot is lifted and the maximum height of the lifts. A final measure concerns exploration. Displacement by walking implies continuous changes in the tilt of the lower leg (as well as of other body segments). With our sensory substitution device the tilt of the lower leg with the device may have an exploratory function in addition to its regular function related to displacement. This is so because the pattern of vibration is a function of the structure of the environment in combination with the position and orientation of the lower leg. As an indication of this exploratory function, we computed and analyzed the range of tilt of the lower leg at a moment at which one may expect to observe exploratory movements: just before the leg was lifted to step on the obstacle. We reasoned that a more pronounced exploration should be evidenced by a larger tilt range.

Materials and Methods

Ethics Statement

This research project was approved by the committee for ethical research of the Universidad Autónoma de Madrid. Written informed consent was obtained from all participants.

Participants

Twenty students and faculty members (17 women, 3 men) participated in the experiment. Their mean age was 20.2 years ($SD = 4.3$). All participants were right footed. None of them had previous experience with this sensory substitution device. In return for their participation, the participants received book vouchers at the end of the last experimental session.

Apparatus

Figure 1 shows the set-up and an individual (in the case of the picture one of the authors) performing the task. The set-up included an approach area of approximately 2.00×0.50 m, six cardboard boxes of different heights (0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 m) placed at one of six possible distances from the participant's starting position (1.00, 1.15, 1.30, 1.45, 1.60, and 1.75 m), and a four-camera motion capture system (Qualisys Inc., Sweden). Figure 2 shows the part of the sensory substitution device that was worn on the leg. This part consisted of 32 actuators attached to the inner side of an adjustable elastic calf support. The actuators were coin-shaped motors (6.0×3.4 mm) that were placed in a zigzag line against the tibialis anterior muscle (parallel to the shinbone). As explained in the following paragraphs, the actuators vibrated as a function of the distance to the first-encountered object in a particular direction.

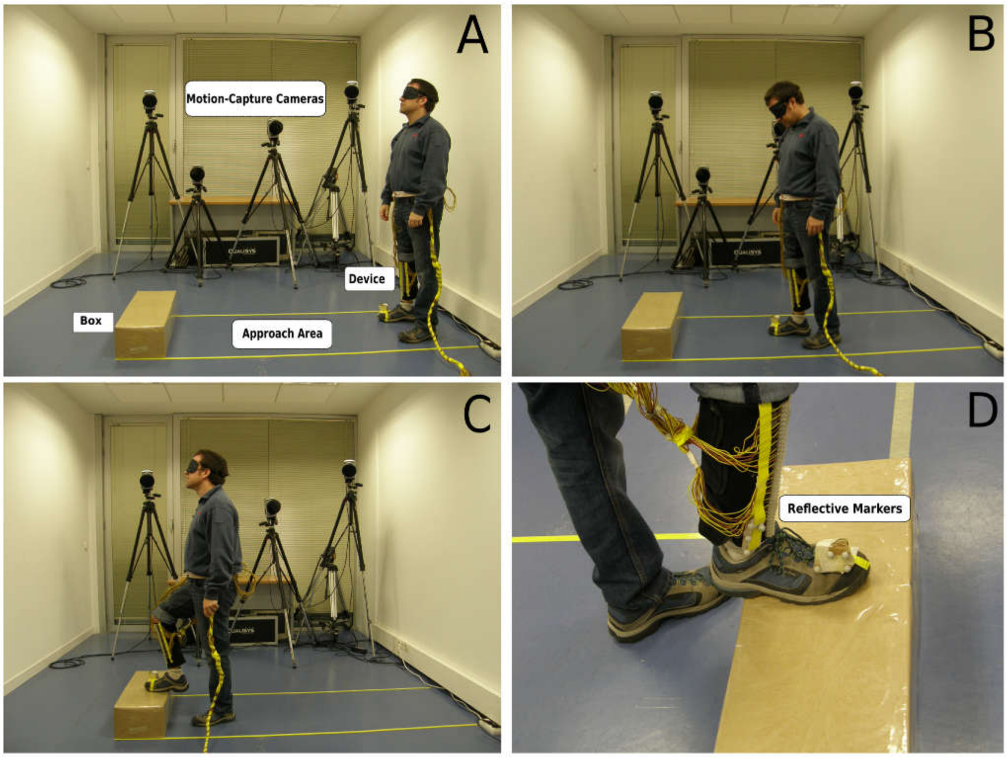

Figure 1. Experimental task and set-up. Participants walked through the approach area (Panels A and B) and aimed to step on the box (Panels C and D). Rigid bodies consisting of four reflective markers were attached to the right foot and to the lower right leg of the participant (Panel D). The position and orientation of these rigid bodies, and hence of the foot and the lower leg, were registered with four motion capture cameras. The experimenter was present during the execution of the task. Participants in the vision group were not blindfolded during training.
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The four Qualisys cameras detected the position and orientation of two rigid bodies (each formed by four reflective markers) at a frequency of 100 Hz. One of the rigid bodies was attached to the right foot and the other one to the part of the device worn on the lower leg. The position and orientation of the rigid bodies were exported from the Qualisys software to MATLAB with the MATLAB plug-in of the Qualisys software. All on-line processing was done on a single PC (Intel Core i7, 3.07 GHz). The output of the on-line processing with MATLAB was an array of 32 driving voltages. These voltages changed with the participants' movements. The digitally-computed voltages were transformed into analog signals with two 16-channel digital/analog (D/A) conversion cards (NI-9264, National Instruments, Texas). The output of the D/A conversion cards was adjusted to the currents required by the actuators with two 16-channel printed circuit boards.

The on-line computations of the driving voltages were based on the positions and orientations of the actuators (derived from the measured position and orientation of the rigid body on the lower leg) in combination with predefined information about the environment (the position and height of the box on a particular trial). In the on-line computations, each actuator was connected to a virtual (i.e., imaginary) sensor. At each moment in time, the driving voltage of the actuator was a function of the distance to the first-encountered object in the direction of the associated virtual sensor. We first describe the details of the distance-voltage relation for a single actuator and then present illustrative examples of patterns of vibration for the array of 32 actuators.

The upper left panel of Figure 3 shows the lower leg with a single actuator for a participant standing straight up in an environment without box. We refer to this situation as the standard situation. The dashed line shows the direction of the virtual sensor associated to the actuator. This direction was constant with respect to the lower leg even if the lower leg moved away from the standard situation. The distance between the considered actuator and the floor in the standard situation is indicated with the actuator specific value d_s (with d standing for distance and s for standard situation). The upper right panel shows a situation in which the lower leg has been tilted forward. In this situation the distance between the actuator and the floor in the direction of the virtual sensor, indicated by d_t (with t indicating that this is a time-specific distance), is shorter than d_s. The digital driving voltage, v_d, was computed from the relation between the changing d_t and the constant d_s, using the following formula: $v_d = 4+6\times(d_s - d_t)$. The lower panel of Figure 3 illustrates the

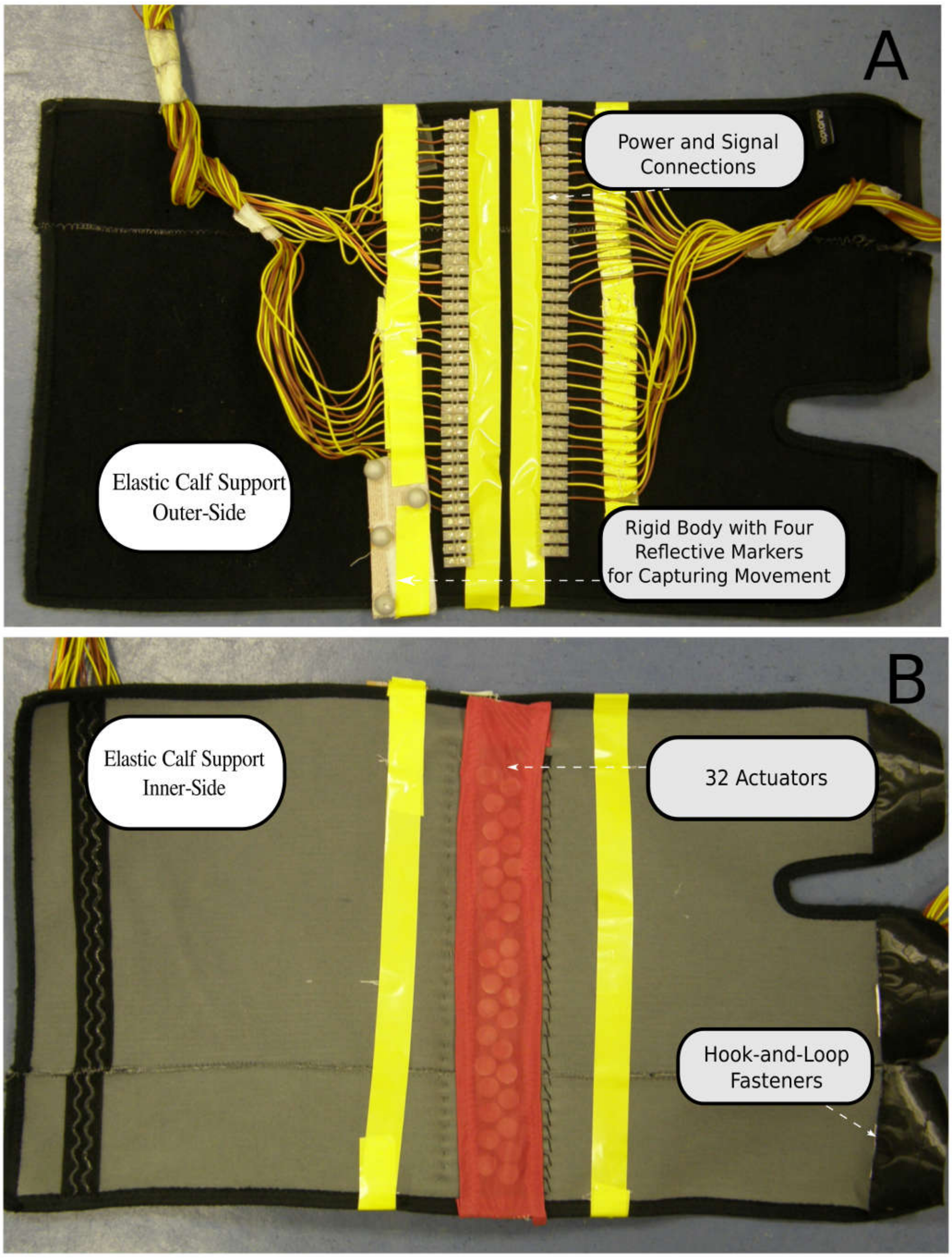

Figure 2. Part of the device worn on the lower right leg. The device included 32 vibrotactile actuators on the inner side of an elastic calf support. The actuators are visible in Panel B through the thin transparent fabric. A rigid body of four reflective markers was attached to the outer side

of the calf support to register the position and orientation of the lower leg. Also attached to the outer side were the cables that provided power to the actuators on the inner side. The rigid body and the power cables are visible in Panel A.
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dependence of v_d on d_s–d_t defined by this formula. Note from the figure that the driving voltage of an actuator was 4 when d_s–d_t = 0 (e.g., in the standard situation). The driving voltage decreased linearly until its minimum of 0 for d_s–d_t, 0 and the driving voltage increased linearly until its maximum of 10 for d_s–d_t. 0 (i.e., when the actual distance was larger or smaller than the one in the standard situation, respectively).

To provide further intuitions about the functioning of the device, Figure 4 shows four patterns of vibration for the array of 32 actuators. The upper part of Figure 4A shows a participant standing straight up without being influenced by the box (i.e., a participant in the standard situation). Because, in such a situation, $d_t = d_s$ for each actuator, the driving voltage shown in the associated lower panel was 4 for each actuator. With the participant's movements, the 32 values for d_s remained constant but the values for d_t changed, giving rise to higher driving voltages for shorter distances (Figure 4B; participant leaning forward) and lower driving voltages for longer distances (Figure 4C; participant leaning backward). The presence of a box in the scanning area also affected the vibrotactile pattern (Figure 4D).

The directions of the virtual sensors with respect to the lower leg, which were a crucial part of these computations, were determined as follows: In the standard situation, the highest actuator had its virtual sensor directed to the point on the ground 100 cm in front of the participant. Likewise, the lowest actuator had its virtual sensor directed to a point on the ground 20 cm in front of the participant. Sensors associated to in-between actuators were proportionally directed to in-between points on the floor. More details concerning a similar device and concerning the relation between the digitally-computed voltages, the analog signals, and intensity of vibration can be found in [12].

Experimental Procedure

Initially the experimenter provided a brief explanation about the sensory substitution device and about the task: "This device includes an array of actuators that vibrate as a function of the first-encountered object on your way. If you are standing straight up, the vibration is homogeneous for all actuators. When the distance to the ground or to an object decreases, the intensity of the vibration of the actuators that are pointing to that surface increases. Conversely, when distance increases, the intensity of vibration of the corresponding actuators decreases. Your task is to walk through the approach area until you detect a box and to step on the box with your right foot. Only forward walking is allowed. A trial ends when you put your foot on the box. The distance to the box and its height will vary randomly." After these instructions, the experimenter attached the device and the first rigid object with markers to the participant's leg and the second rigid object to the right foot. Participants tried the device out during one preliminary trial with full vision. Participants started from the further edge of the approach area on all trials. Trials started with a "go" signal by the experimenter and finished when the participant stepped on the box, or, in case of a failure, displaced the box by kicking against it.

Participants performed three sessions of approximately one hour each on different days. During the first session participants accomplished the pretest and one practice block, during the second session two practice blocks, and during the third session one practice block and the posttest. The pretest, the four practice

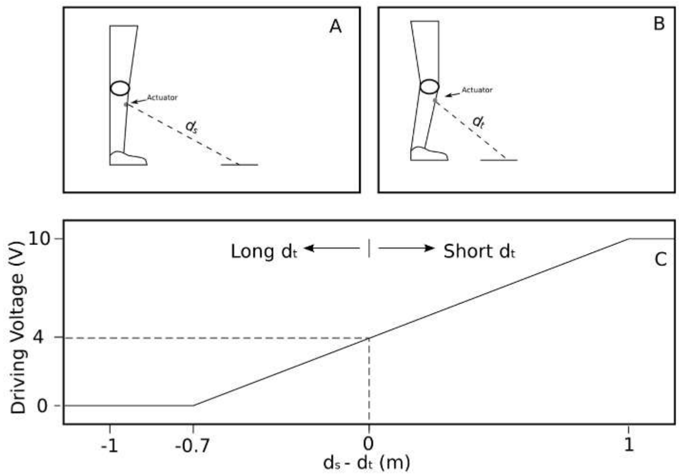

Figure 3. Single-actuator illustration of the distance-voltage relation. The upper left panel shows the lower leg of a participant in the standard situation with a single actuator. The dashed line indicates the direction of the virtual sensor and d_s indicates the distance between the actuator and the floor in that direction. The upper right panel shows the lower leg tilted forward, at a certain moment t; d_t indicates the distance between the actuator and the floor in the direction of the virtual sensor at moment t. The lower panel shows the digitally-computed driving voltage v_d as a function of d_s and d_t: the longer d_t with respect to d_s, the more negative d_s–d_t, and the lower v_d.
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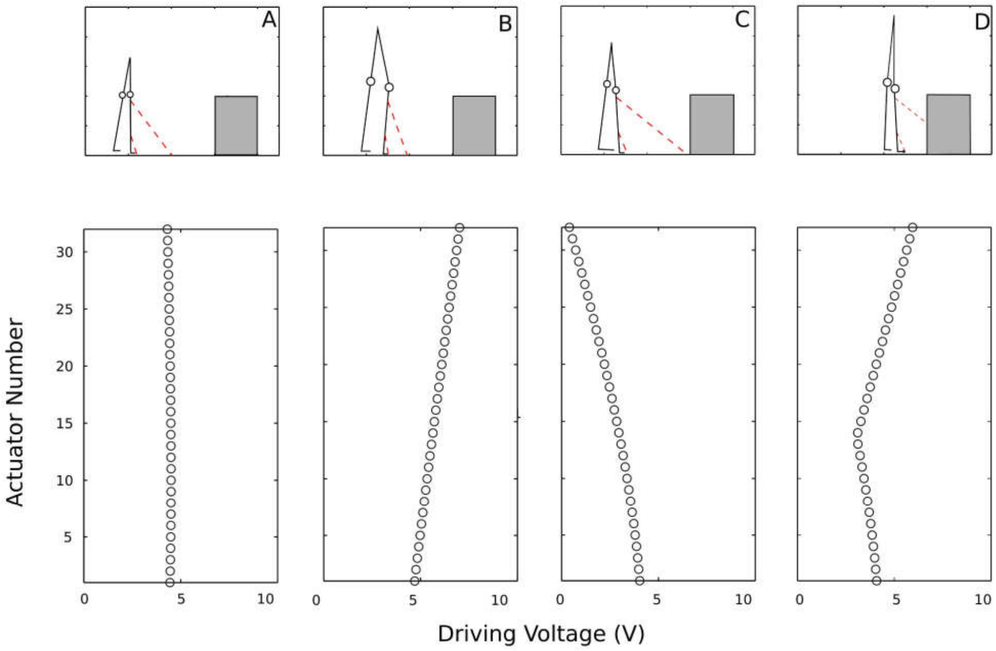

Figure 4. Representation of the 32 driving voltages in four common situations. The upper panels show the position and orientation of the participant's legs (continuous lines with circles representing the knees), the sensing directions of the actuators with the highest and lowest positions on the leg (dashed lines), and the cardboard box (gray area). The lower panels show the driving voltages for all actuators associated to the situations depicted in the upper panels. The vertical axis of the lower panels gives the actuator number, with 1 being the actuator with the lowest position and 32 being the one with the highest position. Four situations are represented (from left to right): A) A participant standing straight up at a sufficiently long distance from the box (the standard situation). In this situation, the driving voltage and hence the intensity of vibration is the same for all actuators. B) A posture with a forward tilt of the lower leg. The distances to the ground are shorter and the driving voltages are higher than in the standard situation. C) A posture with a backward tilt of the lower leg. In this situation the driving voltages are lower than in the standard situation. D) Participant in front of a box. Distances to the first-encountered surfaces are reduced for the virtual sensors directed to the box. As a consequence, the corresponding actuators have higher driving voltages.
doi:10.1371/journal.pone.0098801.g004

blocks, and the posttest each consisted of 36 trials (i.e., 36 attempts to step on the box), obtained from the factorial combination of the six above-mentioned box heights and distances. The time between the first and the third sessions was less than one week. Participants were randomly assigned to one of two groups. The vision group had full vision during the practice blocks and the no-vision group performed the practice blocks while blindfolded. All participants were blindfolded during pretest and posttest. The overall structure of the experiment is illustrated in Table 1.

Dependent Measures

The dependent variables listed in this subsection were obtained from the recorded movements. They were first automatically computed with MATLAB routines and then visually checked (and if necessary corrected) on a trial-by-trial basis. To facilitate the description of the variables, Figure 5 illustrates trajectories of the right foot for several representative trials.

Trial duration. A first dependent measure, trial duration, was defined as the time between the initiation of the movement of the right foot (speed . 20 cm/s) and the moment of the first contact of the foot with the box.

Table 1. Distribution of the 36-trial test phases and the 36-trial practice blocks over the three 1-hour experimental sessions.

Session 1	Session 2	Session 3
Pretest (no vision)	Practice Block 2	Practice Block 4
Practice Block 1	Practice Block 3	Posttest (no vision)

Note. The vision group performed the $36 \times 4 = 144$ practice trials with vision and the no-vision group performed the practice trials without vision.
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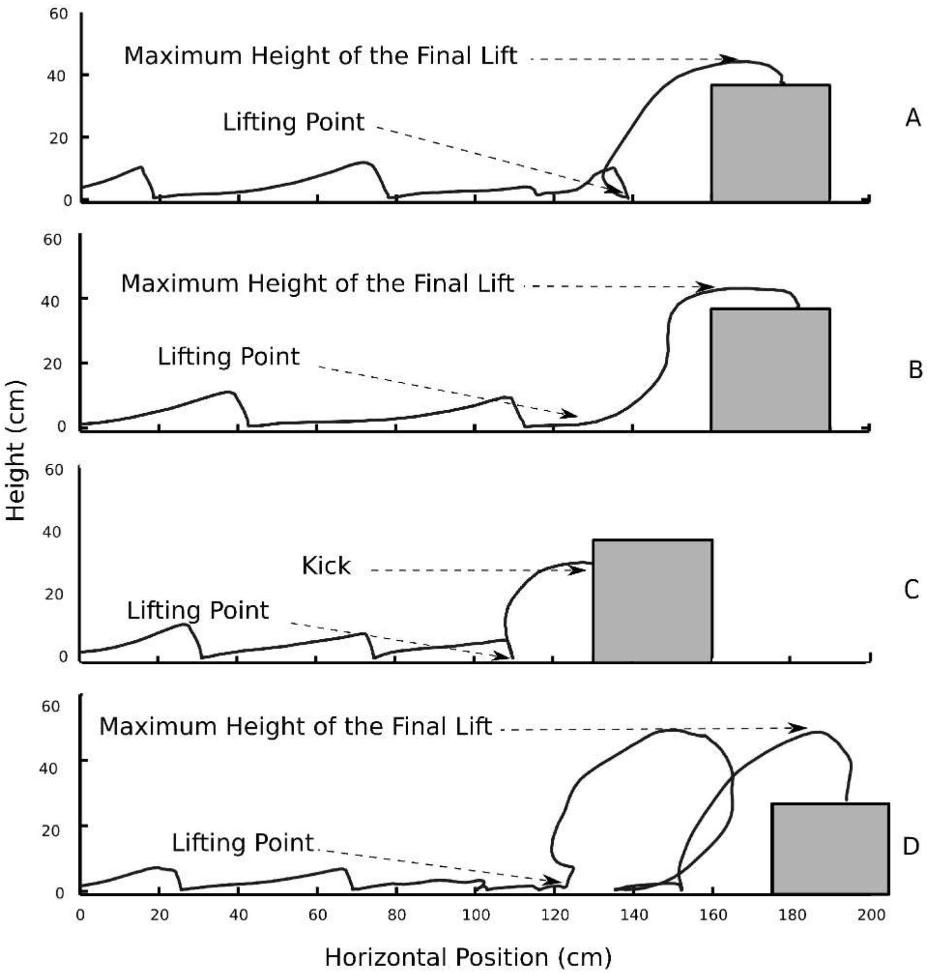

Figure 5. Trajectories of one participant performing four different trials. Solid black curves represent trajectories of the right foot. A) A successful trial without vision, B) a successful trial with vision, C) a trial with a kick after raising the foot, and D) a trial with a false step. As were all other trials with kicks and false steps, the trials represented in Panels C and D were performed without vision. The main points used to compute the dependent variables are identified in each of the shown trajectories.
doi:10.1371/journal.pone.0098801.g005

Kicks and false steps. Kicks, as illustrated in Figure 5C, were defined as cases in which participants contacted the vertical front surface of the box instead of the top of the box. False steps, illustrated in Figure 5D, were defined as cases in which participants lifted the foot to step on the box but in which the ground was contacted again before contacting the box, typically because the step was initiated to far from the box. Note that a strategy-dependent trade off may occur between false steps and kicks. For example, the probability of false steps is reduced at the expense of the kicks if the foot is lifted less frequently (in the extreme, not lifting the foot at all would lead to 0% false steps and 100% kicks). Because of this trade off, we analyzed the total amount of errors in addition to analyzing the kicks and false steps in isolation. The total amount of errors was defined as the sum of the kicks and false steps.

Distance between first lift and box. For each trial with one or more lifts of the right foot, we defined the lifting point as the initiation point of the first lift. This measure is illustrated in all panels of Figure 5.

Height of final lift. For trials without kicks, we determined the maximum height of the final lift, as illustrated in Panels A, B, and D of Figure 5.

Tilt of lower right leg. The range of tilt of the lower right leg was defined as the maximum of the forward tilt minus the

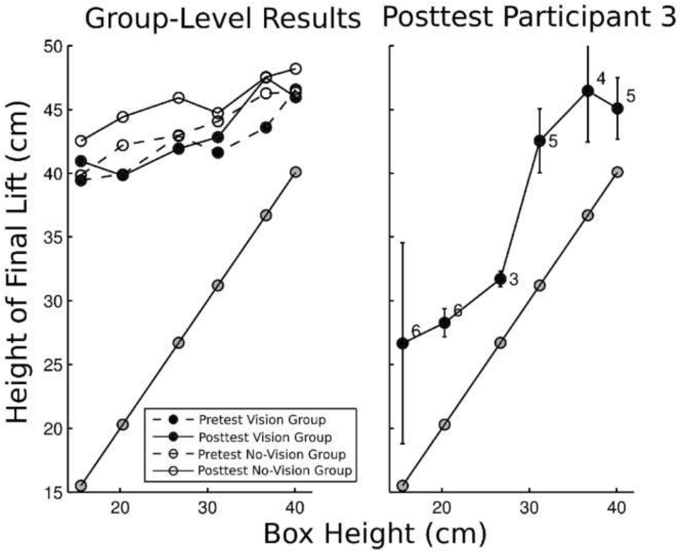

Figure 6. Maximum height of the final lift relative to the height of the box. Left panel: average results per group and per test phase. Right panel: posttest results of Participant 3. Error bars indicate standard deviations; numerals indicate numbers of trials used to compute the average; straight diagonal lines indicate actual box heights.
doi:10.1371/journal.pone.0098801.g006

minimum of the forward tilt, in degrees and with respect to the vertical, during the interval from 2 until 1 s before the first lift. This time interval was chosen because before the lift one may expect exploratory movements and because preliminary analysis showed that in the interval from 1 until 0 s before the lift the variation in the tilt was large due to the actual lifting action.

Statistical Analysis

For each of the dependent variables listed in the previous section, we performed a 2×2 analysis of variance (ANOVA) with practice condition (vision, no vision) as between-subjects factor and test phase (pretest, posttest) as within-subjects factor.

Results

This section first describes the overall performance, then considers the effects of practice, and, lastly, compares the effects of the practice conditions with and without vision.

Overall Description of Performance

Trial duration. On average, the trial duration was 8.24 s ($SD = 2.7$). Participants in the vision group performed the training trials with vision noticeably faster than their pretest and posttest trials without vision (6.6 vs. 7.9 s; $t(9) = 7.12$, p, .001). This difference reached significance also for participants in the no-vision group (7.8 vs. 8.8 s; $t(9) = 2.35$, $p = .04$), who performed the practice trials as well as the pretest and posttest trials without vision.

Kicks and false steps. In the 36-trial pretest and posttest blocks, the mean number of errors (i.e., kicks plus false steps) was 18.8 ($SD = 4.9$). On average, participants had at least one error in 17.1 trials ($SD = 6.9$). The performance with the lowest number of errors consisted of 2 errors in a posttest (kicks in this case). The performance with the highest number of errors consisted of 35 errors in 30 trials of a pretest (30 kicks and 5 false steps). The number of kicks was larger than the number of false steps for all but one of the participants. The participant who showed a reversed pattern had 11 false steps and 6 kicks in the pretest and 10 false steps and 10 kicks in the posttest. Overall, the percentage of pretest and posttest trials without any error was 52.6%.

Distance between first lift and box. The average distance between the lifting point and the box was 22.2 cm in the pretest and 24.0 cm in the posttest. Arguably, however, a better detection of the distance of the box with our sensory substitution device is reflected by a lower standard deviation of the distance rather than by the average distance. This is so because in contrast to a higher or lower average distance, a lower standard deviation indicates the ability to more precisely determine the point at which to lift the foot. In the following, we therefore report analyses with the standard deviation of distance as dependent variable. Let us mention that the same analyses with average distance as the dependent variable did not yield significant results (p. .05).

An alternative measure for the precision of the initiation of the lift is the correlation between the position of the lift initiation and the box. On average, this correlation was 0.73. The relatively high value of this correlation indicates that the sensory substitution device provides a relatively good sensitivity to the distance of the box.

Height of final lift. The average height of the final lift was 42.2 cm ($SD = 4.7$). The correlation between the height of the final lift and the box was 0.29. The moderate value of this correlation indicates that participants did not show as much sensitivity for box height as they did for box distance.

More detail is provided in Figure 6. The left panel of the figure shows the average pretest and posttest results for the two groups. The average height of the final step was only slightly lower for the

Table 2. Results of 2×2 Repeated-Measures ANOVAs on Dependent Variables Defined in Materials and Methods Section.

	Practice Condition		Test Phase		Interaction		
	(Vision *vs.* No Vision)		(Pretest *vs.* Posttest)				
Dependent Variable	***F*(1,18)**	***p***	***F*(1,18)**	***p***	***F*(1,18)**	***p***	***n***
Trial Duration	0.05	.825	20.52	, .001	0.12	.732	1388
Kicks per Trial	0.87	.368	19.34	, .001	1.62	.219	1395
False Steps per Trial	0.91	.356	1.18	.200	3.89	.064	1428
Errors per Trial	0.24	.630	26.35	, .001	4.98	.039	1394
Distance of Lift to Box (SD)	0.69	.410	0.92	.351	6.32	.022	1407
Tilt Range	0.36	.558	7.85	.012	0.32	.578	1237

Note. The ANOVAs were computed on the individual block averages of the listed variables (with the exception of Distance of Lift to Box, which was performed on the SDs; see text for explanation). The number n in the rightmost column refers to the total number of valid trials used to compute the block averages (or SDs).

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low boxes than for the high boxes. Hence, rather than adjusting the final step to the height of the box, participants tended to make high steps. As long as the height of the step was higher than the highest box used in the experiment, this strategy allowed successful performance. For this reason, the results related to box height are less interesting and height-related results are not reported in the following sections.

Let us mention, however, that although the average results discard that the maximum height of the steps is strongly related to the height of the used boxes, results from individual participants occasionally indicate that it may be possible to detect box height with our device. For example, for the block of trials shown in the right panel of Figure 6, the height of the steps appeared to be adjusted to the height of the box ($r = 0.87$, p, .001).

Tilt of lower right leg. On average, 2 s before the moment of the first lift the forward tilt of the lower right leg was 7.8 deg ($SD = 4.7$) and 1 s before that moment the tilt was 5.9 deg ($SD = 6.7$). The average range of the tilt in this interval was 6.9 deg ($SD = 5.3$).

Pretest versus Posttest and Exploration

Table 2 presents the results of the 2 (pretest, posttest)×2 (vision condition, no-vision condition) ANOVAs performed on the individual block averages of the previously described measures. The main effect of practice condition was never significant (all ps . .35), which is not surprising because at least in the pretest one does not expect to observe group differences. We now turn to the main effect of test phase. The variables that showed a significant change from pretest to posttest (p, .05) were trial duration, number of kicks per trial, total number of errors (kicks plus false steps) per trial, and tilt range. Trial duration decreased from 9.10 to 7.39 s, the number of kicks per trial decreased from 0.55 to 0.35, and the number of errors per trial decreased from 0.66 to 0.43. These results indicate that performance with our sensory substitution device improved with practice.

To illustrate the significant change in tilt range, Figure 7 shows the average tilt angles in the pretest and posttest for the vision group (left panel) and the no-vision group (right panel) in the interval between 2 and 0 s before the moment of the first lift. During the last second before the moment of the lift, the angles increased to about 16 to 18 deg, indicating a forward lean at the moment of the lift. From 2 to 1 s before the moment of the lift, the average tilt angles stayed approximately constant at values of about 6 to 8 deg in the pretest (dashed curves), but they showed more interesting patterns in the posttest (continuous curves). In this interval the averaged angles showed a decrease, reaching values below 3 deg for the no-vision group. In the Discussion we will speculate that the larger change in the tilt angles observed in the posttest may evidence a more pronounced exploratory strategy.

Practice with and without Vision

Figure 8 shows the interaction plots for the variables listed in Table 2. Results for the vision and no-vision groups are given with filled dots and open dots, respectively. The majority of the plots indicate the same tendency: Practice without vision led to a steeper improvement than practice with vision. This interaction was significant (p, .05) for the total number of errors and for the standard deviation of the distance between the first lift and the box. The errors per trial decreased from 0.7 in the pretest to 0.4 in the posttest for the no-vision group (pretest-posttest reduction = 0.3) and from 0.6 to 0.5 for the vision group (pretest-posttest reduction = 0.1). The standard deviation of the lift-box distance decreased from 22.3 cm in the pretest to 14.6 cm in the posttest for the no-vision group (pretest-posttest reduc-

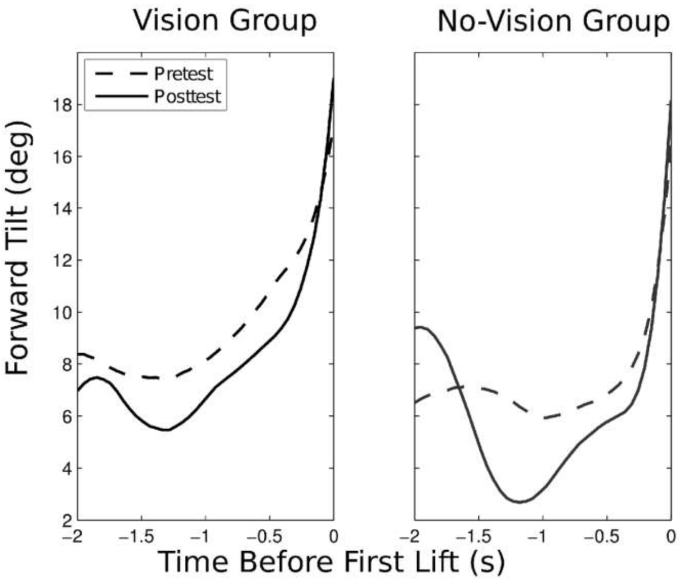

Figure 7. Evolution of the forward tilt of the lower right leg. Shown are the averages of the tilt angles in the final 2 s before the first lift, for the pretest and posttest of the vision and no-vision groups. In the posttest, a decrease in the tilt can be observed between 2 2 and 2 1 s, leading to a larger tilt range in that interval.
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tion = 7.7 cm) but increased from 14.2 to 17.7 cm for the vision group (pretest-posttest reduction = 2 3.5 cm). To summarize these results, practice without vision leads to fewer errors and to a more precise control of the moment of the first lift.

Discussion

The aim of this research was threefold. First, we wanted to determine if it is possible to detect and step on ground-level obstacles with our sensory substitution device on the lower leg. Second, we wanted to know if performance improves with practice. Third, we tested if different practice conditions have different effects on performance. Our results indicate that these questions can be answered affirmatively.

With regard to our first aim, the average percentage of trials that were performed without errors was relatively high given the difficulty of the task (the task was difficult because the location and height of the box were varied from trial to trial). Furthermore, substantial variability was observed among participants: Whereas some participants were very successful, others were less so. In addition to the relatively high average performance, the performance of the more successful participants proves that the sensory substitution system offers enough information to complete the task. This may be interpreted as support for the construction of sensory substitution systems that are lightweight, allow a high level of mobility, and have an on-line coupling of the detected information to the novel stimulation so that users can exploit the new sensorimotor couplings [2,8,22].

One of the factors that may have contributed to the relatively high levels of performance is the fact that the stimulation provided by our device was computed as a function of distance. A substantial number of other devices use light intensity detected by a camera as the basis of the stimulation. Light detected by a camera shows large fluctuations due to changes in illumination and shading effects caused by moving objects. Our visual system has evolved to detect invariant patterns that specify (action-related) properties of interest from these fluctuations [9]. It is unrealistic, however, to expect that perception with sensory substitution devices can reach the sophistication of the visual system. Distances are not affected by fluctuations due to illumination and shading. We therefore believe that distance-based sensory substitution may eventually lead to more successful sensory substitution devices (cf. [12–14,23,24]). Note in this regard that experiments with light-intensity-based devices are often performed in well-controlled environments with predominantly black and white objects (e.g., [5]).

It is interesting to observe that users of our device were able to perform the task despite the poor tactile acuity of the lower leg. In this sense, the strategy that we followed in the development of the device is innovative. Most authors assume that the sensitivity of the skin is among the important criteria to choose the part of the body to place a sensory substitution device [4,25]. Our device, in contrast, is placed on the body segment most relevant to the task at hand. Thus, rather than the sensitivity of the considered body part, what may be important is the suitability, to the task at hand, of the stimulation and of the sensorimotor contingencies provided by the device. Our results show that the design of our device is suited to the control of the final step with regard to the distance of the obstacle.

The evidence for the suitability of the device to control the step as a function of the height of the box is weaker. This may be so because our experimental task allowed a strategy that did not require the detection of information about box height: Participants

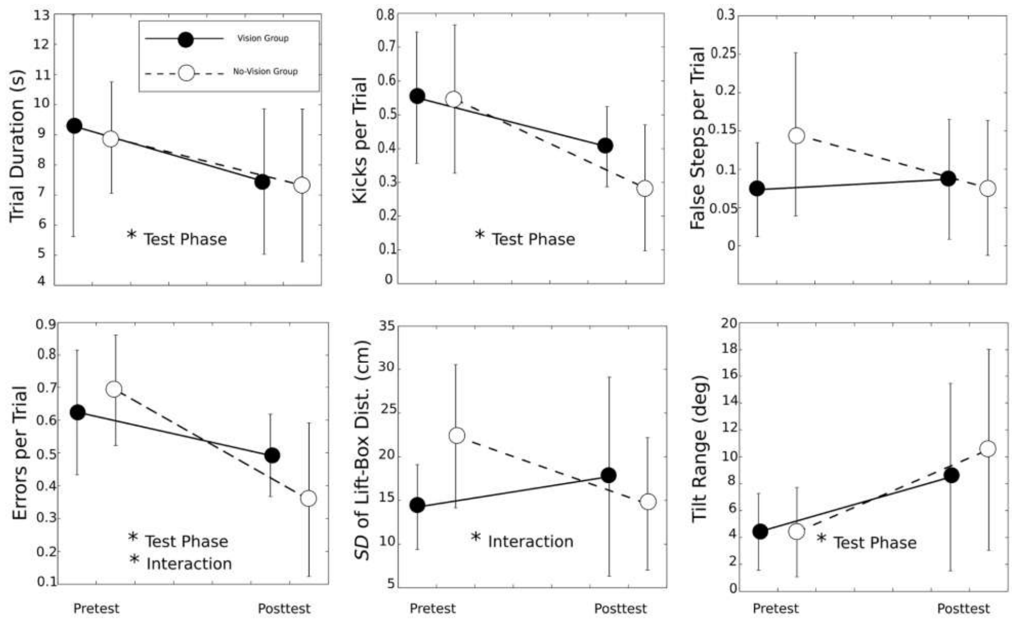

Figure 8. Interaction plots for the main dependent variables. Each graph shows the average value of one variable per test phase and per group. The variable names are indicated on the vertical axes. The significance levels indicated by asterisks correspond to the ones given in Table 2. Error bars represent standard deviations.
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frequently performed steps that were high enough even for the highest box. The fact that participants seemed to use a strategy that kept a part of the performed action constant, possibly because of the difficulty to detect the informational basis of that part of the movement, is reminiscent to a previously reported study about weight perception through dynamic touch [26]. In that study, a deafferented patient showed more reproducible wielding patterns than control subjects with intact proprioception. The constancy shown by the deafferented patient allowed her to estimate the weight of the lifted object visually. Hence, both the deafferented patient in [26] and the participants in our study discovered a way to perform an action successfully while performing a part of the action in way that does not require the typical informational basis of that part of the action–information about box height in our case and proprioceptive information in the case of [26].

With regard to our second aim, we observed that after practice the task was performed faster and with fewer errors (specifically with fewer kicks). This is consistent with a substantial number of previous studies that report effects of practice with sensory substitution devices (e.g., [14–16,18–21]). We also observed a significant effect of practice on the variable tilt range, which indicates the amount of forward-backward tilt of the lower leg with the device (during a certain time interval before the leg is lifted to step on the box). In the pretest, participants showed relatively little variation in the tilt; in the posttest, the range of variation was larger. This pattern may highlight the role of exploration. Changes in the tilt of the leg cause changes in the orientation of the virtual sensors of the device, and, as a consequence, in the pattern of vibration on the leg. Such changing patterns may help the user to detect the environmental properties that co-determine the vibratory patterns (e.g., the presence of an obstacle). Previous studies in the field of sensory substitution that addressed the role of exploratory movements include [12] and [27].

A hypothetical change in exploratory movements with practice can be related to previous studies in the field of dynamic touch. Perceptual and perceptual-motor learning is often associated with a change in which informational variables are detected [28,29]. The detection of particular informational variables, in turn, is associated with particular exploratory movements made to detect these variables [30], leading to the claim that performance improves because learners come to make better exploratory movements [31]. This reasoning indicates that changes in exploratory movements made with sensory substitution devices are consistent with the view that users improve because they come to detect more useful informational variables with the devices.

One may note from the lower right panel of Figure 4 that, with the current configuration of the system, the nearness of an obstacle goes together with an increased vibration of the higher actuators and with a discontinuity (in the figure at Actuator 14) of the change in vibration over the array of actuators. Our results demonstrate that such patterns, their change over time, and/or their sensorimotor coupling to exploratory actions contain information that allows the stepping action. We do not have more precise knowledge about the informational variables that are used by novices and by experts and about how these variables are detected. Achieving such knowledge would be interesting for theoretical reasons and because it may form the basis of more advanced training methods, for instance if this or a similar system is to be used as an assistive device. This is so because, if knowledge about variable use is available, then training methods can be based on the manipulation of the usefulness of the variables typically used by novices so that these graduate more quickly toward the variables typically used by experts (see [32–34] for applications of this methodology in other sensory domains).

With regard to our third aim, practice without vision led to a larger reduction in the number of errors and a larger increase in the precision of the initiation of the final lift than practice with vision. These findings may be related to the guidance hypothesis [35,36]. This hypothesis holds that the more learners rely on some type feedback during practice, the more they come to depend on that feedback. Such a dependency has a detrimental effect on performance when the feedback is withdrawn. During practice with vision, our participants may have depended to a large extent on vision. As a consequence, these participants may not have learned to guide their action on the basis of the vibrotactile information as succesfully as participants that practiced without vision. In short, although vision was not found to prevent learning entirely, our results show an advantage of practice without vision and are hence consistent with the guidance hypothesis.

Let us conclude with two aspects that we consider crucial to the field of sensory substitution. First, we agree with Durette and colleagues [37] that laboratory experiments run the risk of being more of interest to scientists and designers than to users. This is so in part because laboratory studies do not always address practically relevant tasks. With the task chosen in the present study, we have aimed to make a step in a posive direction in this regard. Second, we agree with Lenay and colleagues [8] that there is a need to focus on training programs for coming to be proficient in the use of sensory substitution devices. In this sense our study shows that training without vision has advantages over training with vision.

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Author Contributions

Conceived and designed the experiments: LL DT AB DMJ. Performed the experiments: LL DT. Analyzed the data: LL DT DMJ. Contributed reagents/materials/analysis tools: LL DT AB DMJ. Wrote the paper: LL DT AB DMJ.

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Body-scaled affordances in sensory substitution

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Ecological psychology

A B S T R A C T

The research field on sensory substitution devices has strong implications for theoretical work on perceptual consciousness. One of these implications concerns the extent to which the devices allow distal attribution. The present study applies a classic empirical approach on the perception of affordances to the field of sensory substitution. The reported experiment considers the perception of the stair-climbing affordance. Participants judged the climbability of steps apprehended through a vibrotactile sensory substitution device. If measured with standard metric units, climbability judgments of tall and short participants differed, but if measured in units of leg length, judgments did not differ. These results are similar to paradigmatic results in regular visual perception. We conclude that our sensory substitution device allows the perception of affordances. More generally, we argue that the theory of affordances may enrich theoretical debates concerning sensory substitution to a larger extent than has hitherto been the case.

1. Introduction

1.1. Body-scaled affordances in sensory substitution

A sensory substitution device (SSD) allows the substitution, or enhancement, of the capabilities of a particular perceptual system through an alternative one. Since pioneering devices such as the OPTACON (Linvill & Bliss, 1966) and the TVSS (Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969), technological advances have progressively improved the portability and usability of SSDs (Dakopoulos & Bourbakis, 2010; Jones & Sarter, 2008; Visell, 2009). Even so, a wide generalization of the use of SSDs has not occurred (Spence, 2014).

The majority of SSDs substitute vision through either the tactile or the auditory modality. In these devices, the light intensity detected by a camera is transduced to stimulation patterns ranging from electrotactile or vibrotactile intensity to pitch range. An outstanding example of an auditory SSD is the vOICe (Auvray, Hanneton, & O'Regan, 2007; Proulx, Stoerig, Ludowig, & Knoll, 2008; Striem-Amit, Guendelman, & Amedi, 2012). The vOICe transforms information about the orientation and position of visual edges detected by a camera into sounds with different onsets and pitches.

Beyond the scientific and technical challenge of developing and implementing SSDs, the possibility of substituting a perceptual system raises questions concerning theories of perception and perceptual consciousness. One of the classic questions that have been raised in this regard refers to the conceptual boundary between true sensory substitution and cognitive aids. In true sensory substitution users report perceiving objects out there, in the environment, rather than attending to the stimulation on the sensory surface. The term distal attribution is devoted to this conscious experience of external objects. On the

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contrary, a cognitive aid is a device that translates information about the external world into arbitrary signs. In this case, users perceive the signs and infer the objects through association. Whereas cognitive aids require explicit learning of signs, codes, and the corresponding meanings, true substitution is intended to make distal attribution emerge through a lawful coupling of perception, action, and sensorimotor information, without the explicit learning of codes.

Several authors have claimed that their SSDs elicit distal attribution. Such claims can be found, for example, in the contributions of Guarniero (1974, 1977) with the original TVSS, in several studies with the vOICe (Auvray, Hanneton, Lenay, & O'Regan, 2005; Proulx, 2010; Ward & Meijer, 2010), and in studies with other visuo-tactile SSDs (Segond, Weiss, & Sampaio, 2005; Siegle & Warren, 2010). Other authors have explicitly considered their SSDs to be cognitive aids, as is the case, for example, for the NavBelt (Johnson & Higgins, 2006) and the NAVIG (Kammoun et al., 2012). However, in a large number of cases no clear-cut distinction is made between these two categories. In addition, no generally agreed-upon sensorimotor behavior or technical feature of the SSD has been proposed that allows one to unambiguously differentiate true sensory substitution from cognitive aids.

Distal attribution may be argued to be the result of the mastery of certain sensorimotor contingencies (Auvray, Hanneton, Lenay, & O'Regan, 2005; O'Regan & Noë, 2001). However, given that the majority of SSDs allow an active control of the sensor component and the effector component is lawfully coupled to the sensor component, according to such criteria the majority of SSDs may produce distal attribution. A related criterion to classify a device as to belonging to the true substitution category or the cognitive aid category is the analysis of *how* the sensory information is transformed in stimulation. In true substitution, one may argue, the contingency of the perceiver's movements and the stimulation should be derived from certain physical laws, such as the laws of optics or acoustics, whereas this is not the case for the relation between external objects and the (arbitrary) codes of cognitive aids. Emphasizing the importance of physical laws for perception and action is reminiscent to an approach that, we believe, is of broader relevance to the main theoretical debates in sensory substitution: ecological psychology.

1.2. The control of action and body-scaled metrics

One of the theoretical and empirical fields that have received wide attention from ecological researchers is that of affordances. The concept of *affordance* was coined by Gibson (1979). Affordances for a particular perceiver are the possibilities for action for that perceiver. This means that affordances are environmental properties that are relevant to the perceiver. Proponents of the ecological approach hold that affordances constitute the object of perception.

According to Fajen, Riley, and Turvey (2008), five main features characterize affordances. First, affordances are real. That is, ontologically, affordances are actual properties of the organism-environment system. Second, affordances are animal-specific. This means that they are not intrinsic properties of objects, but relational properties defined with respect to a perceiver. Third, affordances capture the reciprocity of perception and action, meaning that the perception of the environment is in terms of the possible actions that the perceiver can produce and, at the same time, affordances are perceived through active exploration of the environment. Fourth, affordances allow the prospective control of action. That is, by making use of affordances, a perceiver can adjust her behavior to a future state of the environment, lawfully predicted from the current state. Fifth, affordances are meaningful, so that instead of perceiving the environment in neutral terms as extent, mass, and so forth, affordances are perceiver-relevant properties as climbability, catchability, etc.

Fajen et al. (2008) distinguished *body-scaled* and *action-scaled* affordances. The latter concept refers to possibilities for action that are made possible by dynamic action-capabilities of the perceiver. Tasks that have been used to study this type of affordance include the control of braking (Lee, 1976), catching fly balls (Fajen, Diaz, & Cramer, 2011; Oudejans, Michaels, Bakker, & Dolné, 1996), and walking through sliding doors (Fajen & Matthis, 2011; Fajen et al., 2011). Body-scaled affordances refer to properties that are scaled to anthropometric dimensions. Research concerning this type of affordance has addressed stair climbing (Konczak, Meeuwsen, & Cress, 1992; Mark, 1987; Warren, 1984; Wraga, 1999), prehension (Newell, McDonald, & Baillargeon, 1993; Newell, Scully, Tenenbaum, & Hardiman, 1989; Van der Kamp, Savelsbergh, & Davis, 1998), sitting (Mark, 1987), passing under a barrier (Van der Meer, 1997), fitting the hand through an aperture (Ishak, Adolph, & Lin, 2008), and walking through apertures tightly scaled to the inter-shoulder dimension (Warren & Whang, 1987).

How may the key ecological concepts relate to the theoretical debates in sensory substitution and, more particularly, to the debate concerning distal attribution? First, distal attribution is most commonly suggested to concern properties of the world that are independent of the observer, such as the distance or the dimensions of an object as measured in metric units. Because these properties are distal properties (i.e., exclusively belonging to the external world), the distal part of the term distal attribution makes sense. Given that this view is the dominant one in the debate on distal attribution, it is not typically questioned that awareness should eventually be of distal properties.

The ecological shift away from the claim that perceivers are aware of perceiver-independent properties and toward the claim that perceivers are aware of relational properties may reorient the debate concerning distal attribution in the field of sensory substitution. As mentioned, in the ecological view one perceives properties that are best described in terms such as "an aperture that I can pass through" and "a step that I can climb". Because these properties are not exclusive of the external world, the *distal* part of the term *distal attribution* looses part of its meaning. Although a deeper analysis of the concept of affordance is beyond the scope of our article, it is important to note that affordances are instantiated in ecological properties that are scaled to the perceiver. It is also interesting to note that similar claims concerning relational properties have been made in other scientific areas (e.g., in quantum physics; Gomatam, 1999).

A second key claim of the ecological approach is that affordances are perceived in a direct manner, meaning that perception is not mediated by mental representations, inferential processes, or other computational processes (Gibson, 1979; Michaels & Carello, 1981). Although relevant to the debate, this claim cannot be verified empirically. Nevertheless, we believe that it would be illustrative to analyze perception with SSDs using the tools that are typically used in the ecological literature. Such an analysis may confirm that canonical results of the ecological approach in regular perception are also obtained with SSDs. Showing that empirical results with SSDs mirror key empirical results for regular perception may be interpreted as tentative support for the claim that the main theoretical claims of the ecological approach for regular perception are valid also for perception with SSDs. To exemplify this reasoning, the present study aims to replicate Warren's (1984) classic results concerning the stair-climbing affordance with an SSD.

1.3. π-numbers in stair climbing

Warren (1984) asked participants to estimate if they felt able to climb a step in a bipedal manner. His experiments used different step heights and two groups of participants: one *tall* and one *short*. As expected, the steps that were judged climbable were higher for the *tall* group than for the *short* group. Warren proposed a simple biomechanical model to describe the expected maximum step height as a function of the length of the leg. This model, illustrated in Fig. 1, is given by the equation

$$R_c = Leg + ULeg - LLeg. \tag{1}$$

In this equation, R_c refers to the critical step height, *Leg* refers to full leg length, *ULeg* refers to upper leg length, and *LLeg* refers to lower leg length. Eq. (1) allows one to derive the value of R_c from anthropometric values. One may assume that the value of R_c corresponds to the step height that leads 50% of affirmative climbability judgments.

Warren (1984) showed that the climbability affordance can be described with a dimensionless number called critical π-number. The critical π-number (π_c) refers to the maximum height that a participant is able to climb in a bipedal manner scaled to her leg length. This number can be defined as

$$\pi_c = R_c/L. \tag{2}$$

Warren observed that the group differences in the climbability judgments disappeared after scaling the height of the steps to the leg length of participants: Both experimental groups showed the expected value of $\pi_c \approx 0.88$.

In the present study, we test if participants using an SSD are able to perceive affordances. More specifically, we test if participants estimate the climbability of steps in the same way as the participants in Warren's (1984) regular visual perception study. We hypothesize that perception with an SSD shares the body-scaled nature observed for visual perception.

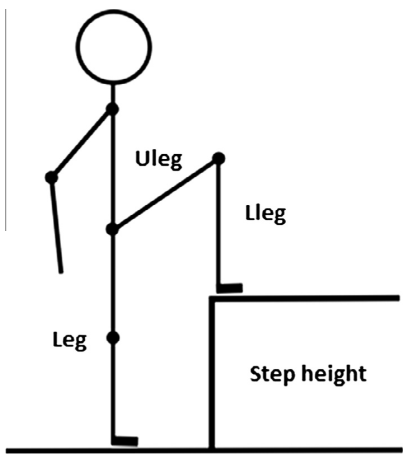

Fig. 1. Biomechanical model of stair climbing. Adapted from Warren (1984).

2. Materials and methods

2.1. Participants

Two groups of eight male participants performed the experiment. Individuals in the *tall* group had a mean height of 182.5 cm (*SD* = 1.3 cm) and were taller than the 75th percentile for height reported in the tables of the Centers for Disease Control and Prevention (CDC, 2002). Individuals in the *short* group had a mean height of 169.1 cm (*SD* = 2.2 cm) and were shorter than the 25th percentile for height (CDC, 2002). All participants signed an informed consent form prior to the experiment. The research program was approved by the local committee of ethical research (CEI 52-957).

2.2. Design

Following Warren's (1984) design, two independent variables were considered. The first independent variable was the height of participants (i.e., the *tall* and *short* groups). The second independent variable was the height of the to-be-judged steps. Seven step heights were used, ranging from 45 to 105 cm. Our steps were similar those used by Warren, who used seven steps heights ranging from 50.8 to 101.6 cm. In our experiment, each step height was used five times, resulting in 7 (step heights) × 5 (repetitions) = 35 trials per participant. The order of the trials was randomized per participant.

2.3. Apparatus and setup

Fig. 2 illustrates the experimental setup. The setup included an exploration area of approximately 400 × 80 cm, a raised platform (i.e., the step) located 50 cm beyond the end of the exploration area, and a four-camera motion-capture system (Qualisys Inc., Sweden).

Participants wore a vibrotactile SSD that was initially designed for previously reported experiments (Díaz, Barrientos, Jacobs, & Travieso, 2012). The SSD consisted of a vertical array of 24 coin motors whose vibration was a function of the distance to the first-encountered object in a frontal body-referenced direction. The vertical array of actuators was located between the top part of the chest and the navel, about 4 cm to the left of the sternum (from the perspective of participants). A rigid body (a piece of cardboard with reflective markers) was also attached to the chest (near the actuators). The motion tracking system continuously registered the position and orientation of the rigid body formed by the reflective markers and exported these measures to Matlab.

Self-developed Matlab routines used the imported position and orientation of the rigid body to compute the position and orientation of the participant, and hence of each actuator. The position and orientation of each actuator, in turn, were used to compute the distance from the actuator to the first-encountered object in the pre-established frontal direction (see Fig. 3). In this experiment, the first-encountered object was either the floor or the step. As mentioned, the driving voltage of each

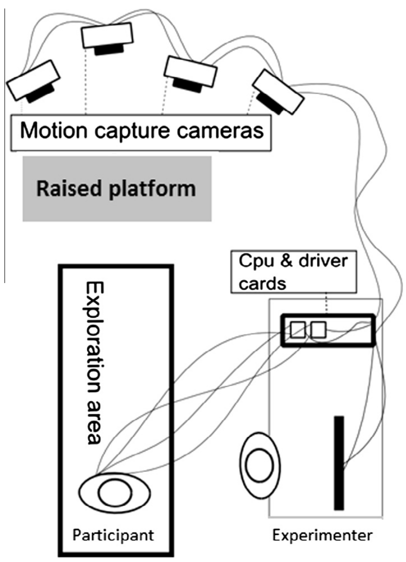

Fig. 2. Experimental setup.

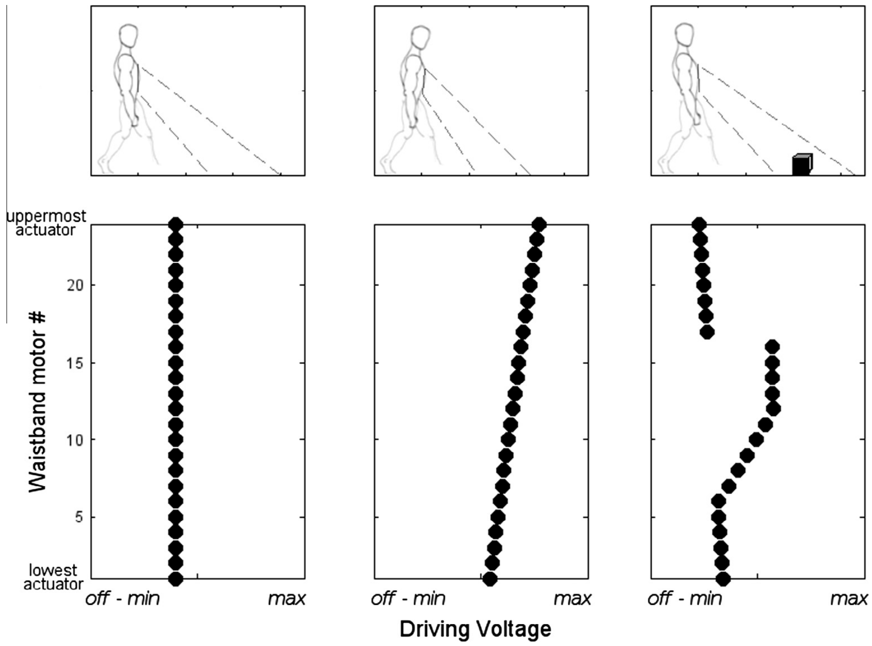

Fig. 3. Schematic representation of the functioning of the SSD. Upper panels show participant positions and the ground range that is "in sight". Lower panels show the corresponding activation of the vibrating motors.

actuator was computed as a function of the distance to the first-encountered object; the nearer the object, the higher the driving voltage. Finally, the driving voltages were sent to the coin motors. The system cycled through the computations with a frequency of about 20 Hz.

Fig. 3 illustrates the functioning of the SSD in three situations. The panels on the left illustrate a user standing straight up in a situation without a step. In this situation, the sensory direction of the highest actuator was oriented to a point on the ground 3.0 m ahead, the lowest actuator was oriented to a point on the ground 1.5 m ahead, and the in-between actuators were oriented to in-between points on the ground. The lower left panel illustrates that, in this situation, a constant low voltage level was used for all actuators. When the participant moved, the orientation and position of the actuators and the associated body-referenced sensory directions changed, resulting in changes in the distances to the floor (or to the step) along the sensory direction of the actuators. The middle panels of Fig. 3 show a situation in which the participant leaned slightly forward, resulting in shorter distances and hence higher driving voltages, especially for the higher actuators. The right panels show a situation with a step. In this situation, the distances to the first-encountered object and the associated driving voltages changed in a less homogeneous manner over the actuators than in the situations shown in the left and middle panels.

A more detailed description of the used SSD is provided in Díaz et al. (2012). An alternative (portable) version using a Microsoft Kinect sensor (without the need of external position tracking and virtualization) is described in Cáncar, Díaz, Barrientos, Travieso, and Jacobs (2013; cf. Lobo, Travieso, Barrientos, & Jacobs, 2014).

2.4. Procedure

Participants were first measured anthropometrically, allowing us to calculate the biomechanical model. Then, they received the following instructions: "The vibration of the actuators is a function of the distance to the ground. The vibration is uniform if you are standing straight up and there is a flat surface in front of you. If you lean forward, the vibration becomes more intense because the actuators get closer to the ground; if you lean backward, the vibration becomes less intense because you are not focusing on the ground. Similarly, if an obstacle is present, the area of the array that points toward the object vibrates more intensely because the distance between the actuators and the nearest object is reduced. Now I am going to present you steps of different heights. At the end of each trial, you will be asked to tell me if you think you are able to climb them without using your hands. You should not leave the exploration area during the trial. Once blindfolded I will tell you if you are about to leave the exploration area, so you can avoid leaving it." To clarify the explanation we used the images presented in Fig. 3.

Before the actual experimental trials, nine practice trials were performed with three repetitions of the smallest (45 cm), medium (75 cm), and highest (105 cm) steps. In these trials, a wooden platform that was adjustable in height was used, and participants perceived both through the SSD and through regular vision (i.e., they were not blindfolded). Participants were not allowed to touch the steps at any moment. These practice trials were immediately followed by the 35 experimental trials. Each trial lasted 30 s. Participants started at the furthest end of the exploration area, and they were allowed to walk back and forth in the area. The experimenter warned participants verbally when they closely approached one of the edges of the exploration area, in order to avoid that they left the area. When the 30-s trial ended (i.e., when the vibration stopped), participants made a forced-choice judgment concerning the perceived bipedal climbability. No feedback was given. In the experimental trials participants were blindfolded and virtual steps were used. The virtual steps affected the vibration as described above without being physically present. The physical presence of the steps was not necessary because, during the experimental trials, participants were blindfolded and did not have physical contact with the steps.

3. Results

We performed a two-way ANOVA on the proportion of trials in which participants judged the step to be climbable in a bipedal way. The within-subjects factor was the height of the step (seven levels) and the between-subjects factor was group (tall vs. short). Significant main effects were observed for step height, $F(6,84) = 27.64$, $p < .001$, and group, $F(1,14) = 5.41$, $p = .04$. The interaction was not significant: $F(1,32) = .95$, $p = .34$. As can be seen in Fig. 4, as the steps increased in height, the proportion of steps that were perceived as climbable progressively decreased. The figure also shows that this proportion was higher for the *tall* group than for the *short* group.

To illustrate the stair climbing affordance as done by Warren (1984), it is necessary to establish the height with 50% affirmative judgments (which is assumed to correspond with the critical step height, R_c, as defined in Eq. (1)). To do so, we fitted logistic functions to the probability data, using the equation

$$p_{(\text{climbable})} = \frac{1}{1 + e^{-a+bx}}. \tag{3}$$

Fig. 5 shows the fitted curves for the *tall* and *short* groups. We performed a t-test on the critical step heights (R_c) that were obtained from the logistic curves of individual participants. The effect of group was significant: $t(14) = 2.12$, $p = .003$. The *tall* group indeed judged that they could climb higher steps ($M = 84.39$ cm, $SEM = 3.57$) than the *short* group ($M = 74.85$ cm, $SEM = 2.76$).

We next rescaled the results as the ratio of step height by leg length. We performed the same logistic fits on the rescaled data as on the original data. Fig. 6 shows the resulting curves. A t-test on the individual critical π-numbers (π_c) did not show a significant group difference: $t(14) = 0.75$, $p = .46$. Finally, we performed a t-test to check if our overall π_c was different from .88 (the value reported by Warren, 1984). The overall π_c in our sample was not significantly different from .88: $t(15) = 0.99$, $p = .34$. In our case, π_c was 0.91.

In addition to the similarity of the observed values of π_c, it is interesting to note that our response curves and the ones reported by Warren (1984) differed in the sense that our curves were less steep. For example, whereas Warren reported 0%

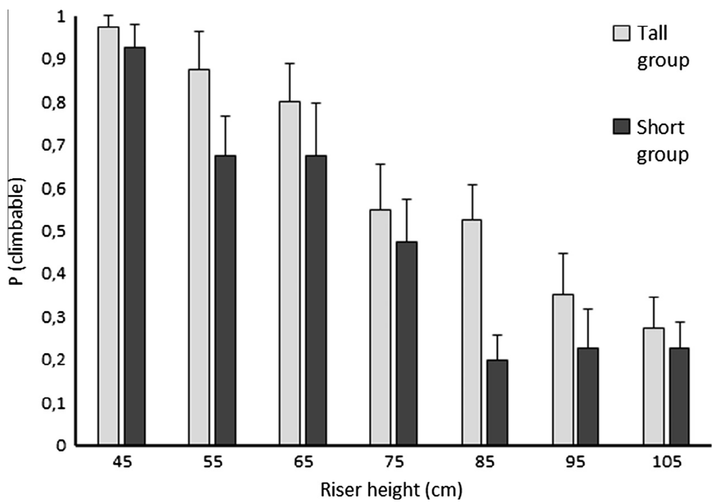

Fig. 4. Proportion of affirmative judgments as a function of step height and group.

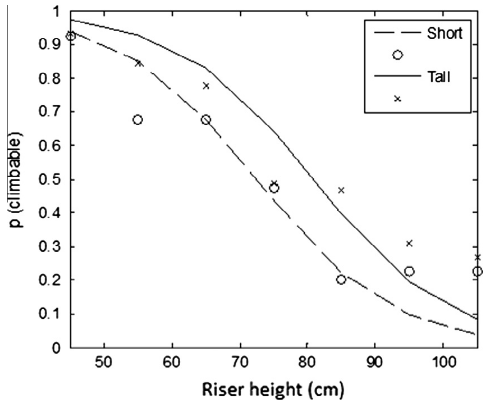

Fig. 5. Logistic fits of *p*(climbable) as a function of step height for both experimental groups.

and 100% of climbable responses for step heights of 101.6 and 50.8 cm, respectively, we did not observe percentages as low as 0% nor did we observe percentages as high as 100%. This difference can be interpreted as reflecting the lower acuity of perception with an SSD as compared to regular visual perception. Note, finally, that whereas our data show a relatively continuous decline of the percentage of climbable responses with riser high for the *tall* group, the decline seemed to be slightly less continuous for the *short* group. We do not have an explanation for this latter finding.

4. Discussion

The rationale of the present study was to test if SSDs allow the perception of affordances. As a case study, we addressed the perception of climbability through a vibrotactile SSD. It was shown that tall users of our device have a higher mean threshold of climbable steps than short users. However, when the height of the steps is scaled to the length of the leg of the users, then tall and short users do not differ in the height that they perceive as climbable. In sum, perception with our SSD is not of a primary quality of the object, height, but of a relevant relational property, climbability. A similar distinction between primary and secondary qualities, in a different scientific area, was addressed by Gomatam (1999).

With respect to the critical π-number of this affordance, our results for perception with an SSD did not differ significantly from those reported by Warren (1984) for visual perception, establishing the π-number for critical step height around $\pi_c \approx .88$. Given that the proprioceptive components of the tasks are not different, the perception of the steps does not appear to differ between regular vision and SSD perception, at least on the crucial aspect considered in our analysis. Our conclusion, therefore, is that our vibrotactile SSD allows the perception of body-scaled affordances, albeit with less acuity than regular visual perception. The observed similarity between different ways of perceiving is reminiscent to Gibson's concept of

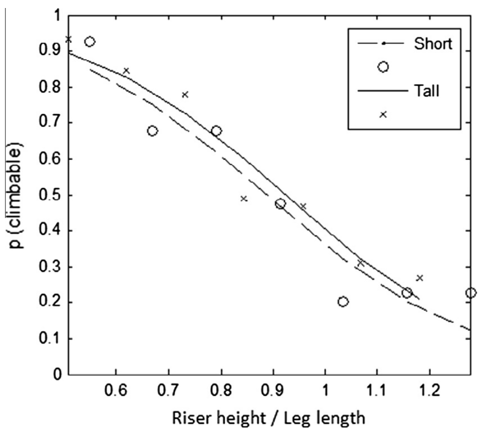

Fig. 6. Logistic fits of *p*(climbable) as a function of step height divided by leg length for both experimental groups.

perceptual systems and, in particular, with his idea that "the pattern of the excited receptors is of no account" (Gibson, 1966, p. 4).

Relatedly, in the introduction of this article we have argued that adopting key ecological tenets, such as the claim that perception is of affordances, may be of relevance to theoretical debates in the field of sensory substitution. Let us also speculate that an objective measure of π-numbers of either action-scaled or body-scaled affordances may be a useful part of tests that aim to classify SSDs as producing true sensory substitution (i.e. distal attribution) or as being a cognitive aid. Our main argument is that the perception of affordances emerges from active exploration, the resulting sensorimotor contingences, and the biological demand to perceive relevant relational properties. In so doing, a stable objective measurement can be obtained in the form of dimensionless informational numbers that can be tested experimentally. A cognitive aid that, say, indicates the presence of a particular object or letter with a particular vibratory code, might be expected to be less likely to produce the perception of body-scaled affordances.

In addition to concluding that body-scaled affordances are perceived with our SSD, one may consider the question of *how* such affordances are perceived. The main ecological tenet in this regard is that affordances are perceived directly. We are aware, however, that assuming that the observed π-number provides evidence for direct perception might not result convincing to many, as the skeptic argument may always be held. Even in regular vision, the skeptic concerning direct perception may always considered perception a compositional process that starts with minimal units of information that are later integrated and added to secondary properties in an automatic and unconscious manner, perhaps in a computer-like fashion via symbol manipulation. Likewise, possible claims about direct perception with SSDs are always open to criticism, which may mirror the skeptic argument in the case of regular vision (Fodor & Pylyshyn, 1981; cf. Turvey, Shaw, Reed, & Mace, 1981). If, on the other hand, one chooses to place the burden of proof on the skeptic, one may also argue that replicating a sufficient number of key ecological results, such as the observed π-numbers, sets perception with SSDs in reference to direct perception at the same status as regular visual perception.

Although the main topic of the present article is the perception of affordances, we now briefly address another main concern of ecologically inspired research: the informational basis of actions. According to Cesari, Formenti, and Olivato (2003), the perceptual parameter that defines the initiation of the stepping action is the angle between the line from the tip of the foot to the bottom of the step and the line from the tip of the foot to the top of the step. These authors showed that different groups of perceivers with regular visual perception initiated the stepping action when this angle reached the value of 68.3°, which is to say, when the height of the riser was 2.5 times the distance to the step. Such findings, related to the informational basis of actions, may have important implications for the design of SSDs: If one aims to facilitate the control of the stepping action it may be crucial to design SSDs that allow the detection of the angle considered by Cesari et al. An example of an SSD designed for stepping on obstacles—although not inspired by the results of Cesari et al.—can be found in Lobo et al. (2014).

To summarize, we belief that basing further work with SSDs on the conceptual background of the ecological approach to perception, which includes the notion of affordances, may improve both the usability of the devices and the scientific knowledge of the involved perceptual and behavioral processes.

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From: Julie Weast-Knapp and Gert-Jan Pepping, Editors of *Studies in Perception and Action XIV*

Subject: Letter of acceptance for publication

Dear authors,

Thank you again for your submission entitled *Sensory Substitution and Walking Toward Targets: An Experiment With Blind Participants.*

Your revised abstract for a poster presentation has been received and peer-reviewed by a member of the conference scientific committee.

We are pleased to inform you that your submission has been accepted for publication in the 2017 conference poster-book *Studies in Perception and Action XIV* (to be published in 2017 by Psychology Press (Taylor & Francis)).

Thank you for your contribution. We look forward to your presentation at the conference.

Sincerely,

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Studies in Perception & Action XIV
J. Weast-Knapp & G-J. Pepping (Eds.)

Sensory Substitution and Walking Toward Targets: An Experiment With Blind Participants

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The most widely-used mobility aid for the blind is the long cane. A main challenge for improving the mobility of visually impaired and blind people is the development of electronic travel aids (ETAs) that improve mobility beyond the mobility allowed by the long cane (Hersch & Johnson, 2008). In this chapter, we argue that the design of ETAs crucially depends on our conception of what mobility is, or, formulated in an ecological way, on our understanding of the informational guidance of movement. An experiment is presented to illustrate this claim.

ETAs consist of three components (Visell, 2009). First, a sensory component that detects certain information from the environment that is not available to the user of the ETA because of the loss of sight. Second, a component that transforms the detected information into the information to be delivered to the perceiver. And third, a display component through which the novel information is actually delivered. With regard to the display component, the device tested in the present experiment applied vibrotactile stimulation to the abdomen by means of 72 actuators. In the sensory component, the device relied on the distance to the nearest surface in the environment, having a total horizontal field of view of 60º. Finally, the device used a linear function to transform distance into vibration: the closer the object in the direction associated to a particular actuator, the more intense the vibration of that actuator.

The same device has previously been used in a series of experiments by Lobo, Travieso, Jacobs, Rodger, and Craig (2017). The device was designed to allow for active information detection. This aspect of the design was motivated by the ecological view that locomotion trajectories, rather than being planned, emerge dynamically from the online coupling of information to action. The ecological focus on information and emergence differs from the focus on spatial representations (Schinazi, Thrash, & Chebat, 2016) and on brain plasticity (Maidenbaum, Abboud, & Amedi, 2014) of other studies concerning sensory substitution.

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In the reported experiment, blind users of the device walked toward targets. An outstanding non-representational model for the visual control of walking to targets is the one by Fajen and Warren (2003). Their model illustrates how the trajectories followed by participants may emerge from a direct coupling of action parameters to simple optical variables. Our sensory substitution device provided haptic analogues of the optical variables that were important in Fajen and Warren's model: the body-referenced angle of the target and the distance to the target. We hypothesized that our device permits successful performance because it allows the detection of the relevant informational variables.

Method

Six blind individuals participated. Their mean age was 54.3 years (*SD* = 10.9). None of them had previous experience with the sensory substitution device.

The 72 vibrotactile actuators that were attached to the abdomen were distributed in three horizontal rows of 24 actuators each. The total field of view of 60º was divided in 24 segments of 2.5º associated to the individual actuators. Each actuator vibrated if the target was located in its 2.5º segment of the field of view. The equation used to transform distance in vibration was: $V = V_{max} - 0.12 \times D$, where V is the voltage level, expressed as a percentage of the maximal voltage level V_{max}, and D is the participant-target distance (in cm). The vibrotactile information was contingent upon the participant's exploration. To achieve this, the participant's position was recorded (at 100 Hz) with a motion capture system (Qualisys AB, Sweden). The detected position and orientation of the participant relative to the target was used to compute the voltage levels. Note that the current device did not include actual distance sensors. A related device, described by Cancar, Díaz, Barrientos, Travieso, and Jacobs (2013), did actually detect the relevant distances.

Participants were asked to walk to a target. Six target locations were used, which differed with regard to their initial distances and heading directions (3 m and ±15º, 4 m and ±10º, and 5 m and ±5º, respectively). The target was virtual: although the target location determined the vibration, the target was not physically present. Participants verbally indicated when they believed that they had arrived at the target location. Participants completed two repetitions of each of the six experimental trials as well as three familiarization trials (2 m and ±30º and 6 m and 0º).

As mentioned, the intensity of vibration increased when the distance to the target was reduced. In addition, different actuators were active depending on the relative angular location and the angular size of the target. For example, when participants rotated in a clockwise direction, the vibration on the abdomen moved in a counterclockwise (leftward) direction. The vibratory information hence specified target direction and distance.

Results and Discussion

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On 70 of the 72 trials (97.2%), performance was successful in the sense that participants arrived at the location of the target. The two unsuccessful trials (2.8%) and one trial with recording errors (1.4%) were not used in the analysis. An example of a successful trial is shown in Figure 1. Note the oscillatory pattern in the right panel of the figure. This left-to-right oscillation in the vibratory flow occurred because, while participants moved forward, they performed exploratory yaw rotations of the upper body.

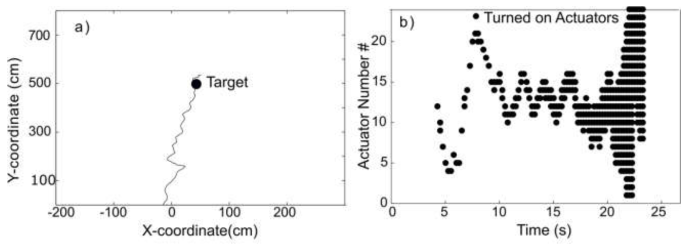

Figure 1. One-trial example of the (a) two-dimensional participant position and (b) changing pattern of vibration during the trial. Not shown is the rotation of the upper body.

The average spatial error (the Euclidean participant-target distance at the end of the trial) was 67.89 cm (*SD* = 19.87). The mean trial duration was 33.97 s (*SD* =15.20). Participants performed an average of 18.4 (*SD* = 7.4) oscillatory movements per trial. The mean amplitude of the oscillations was 28.3º (*SD* = 13.4). The amplitude of the last oscillation before the decision was 7.1º (*SD* = 3.7). We did not observe a significant effect of the initial target distance on the number of oscillations and neither on the mean amplitude of the oscillations: $F(2,66) = 0.03$, $p = .97$, and $F(2,66) = 0.08$, $p = .92$, respectively. The trial duration was inversely related to the spatial error: the longer a trial, the larger the error ($r = .40$, $p < .001$). On average, participants walked 18.31 cm/s. This walking speed is substantially lower than the typical walking speed of visually impaired individuals with a long cane (Johnson, Johnson, Blasch, & de I'Aune, 1998).

We compared the performance of the blind participants in the present experiment to the blindfolded sighted participants in a corresponding experiment by Lobo et al. (2017). The blind participants had larger spatial errors (67.89 vs. 39.62 cm; $t[6.5] = 3.2$, $p = .02$). However, this difference is difficult to interpret because the blind participants were older (54.3 vs. 27.6 years, $t[5.9] = 5.6$, $p = .001$) and had a clear disadvantage in terms of general motor abilities. We did not observe differences between the blind and blindfolded participants in other performance-related variables: angular error, trial duration, total distance covered, walking speed, and amount and amplitude of exploratory rotations. Lobo et al.

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(2017) observed similar exploratory rotations in an orientation task with a fixed participant-target distance.

To summarize, the blind participants in the present experiment successfully reached the target in almost all of the trials. This high level of performance indicates that the tactile sensory substitution device allowed the detection of relevant informational variables—analogues of which are usually detected by the visual system. By coupling these variables to action parameters, the locomotion trajectories may have emerged in an online fashion (Fajen & Warren, 2003), without need for trajectory planning on the basis of spatial representations (Schinazi et al., 2016). If this suggestion is correct, then the design of future ETAs should focus on the possibility to actively detect the variables implied in the relevant information-action couplings.

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